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# The Effect of Gap Spacing Between Solar Panel Clusters on Crop Biomass Yields, Nutrients, and the Microenvironment in a Dual-Use Agrivoltaic System

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**THE EFFECT OF GAP SPACING BETWEEN SOLAR PANEL CLUSTERS ON CROP BIOMASS YIELDS, NUTRIENTS, AND THE MICROENVIRONMENT IN A DUAL-USE AGRIVOLTAIC SYSTEM**

A Thesis Presented

by

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# ABSTRACT

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Agrivoltaic (AV) systems are dual-use land systems that consist of elevated solar panels with crops grown underneath. They offer a solution to the increasing demand for food production and clean renewable energy. The main concern regarding AV systems is the reduced availability of light to crops below the panels. Research to date shows that AV systems are quite productive with total energy and crop production exceeding the outputs of either solar farms or crop production alone. Research also shows that solar panels affect the microenvironment below the panels. The research on AV systems so far considers altering panel density to increase radiation to the crops by varying the distance between rows of panels in an AV solar array. This study examines the crop outputs for Swiss chard, kale, pepper, and broccoli in an AV system with different gap spacings of 2, 3, 4, or 5 feet (AV plots) between panel clusters within rows to determine how much spacing between solar panels is optimal for crop production by comparing these system yields to full sun crop production. This study also examines the effect of the AV system on crop nutrient levels, on soil water content, and crop leaf temperature below the panels. Ultimately, the biomass crop yields of AV plots are restricted significantly for Swiss chard, kale, or pepper compared against the full sun control plot yields but not for

broccoli stem + leaf yields. The 4-ft or 5-ft gap distances between panels yield the highest crop biomass of the AV shaded plots. Nutrient levels tend to increase with more shade but the trend is only significant for Swiss chard nitrogen and phosphorus concentrations, pepper potassium concentrations, and broccoli phosphorus concentrations. For soil water content it is found that panels have some effect on evapotranspiration and rainfall redistribution at the soil level. Leaf temperatures in the AV plots are lower than leaf temperatures in the control plots on sunny days but not on cloudy days.

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# CHAPTER 1

# LITERATURE REVIEW

## 1.1 Introduction

With an expanding population and growing industry, there is increasing need for alternative and innovative methods of food and energy production (Amaducci et al., 2018). The non-renewable nature and negative side-effects, such as gaseous carbon emissions, of using fossil fuels for energy has prompted a change in this direction (Dinesh and Pearce, 2016). Moreover, new policy surrounding energy consumption and production is contributing to the demand as well (Amaducci et al., 2018). For example, the European Union plans to have renewable resources account for 20% of the energy that it produces by 2020 (Amaducci et al., 2018). Of the different types of renewable energy such as bioenergy, wind power, geothermal, hydropower, and solar power, solar power is one of the most promising. However, solar energy does have a substantial land requirement that can compete with agricultural land especially because solar panels need near flat and clear land. A traditional solar farm produces about 1 MW of energy per every two hectares of land (Santra et al., 2017). Its land requirement, however, compared to other comparable renewable energy options is more efficient (Malu, 2017). For example, bioenergy, which uses biomass to produce energy, is a less efficient use of land when considering how much energy is produced per unit of land area (Dupraz et al., 2011). For example, 1600 hectares of typical pine plantations would produce about 1 MW of power a year (Ashton et al., 2014). Furthermore, the potential to use biomass for energy instead of as a food source may create issues that solar energy would not. For example, if biomass is to become a common fuel source, food prices of the crops displaced by the biomass crops could also increase, an issue that will be problematic as food insecurity increases especially in underdeveloped countries (Dupraz et al., 2011). Subsequently, the use of solar energy is growing and will continue to grow more popular. For instance, by the year 2050 solar energy alone will account for approximately 16% of energy produced in the world according to the International Energy Agency (IEA) (Malu et al., 2017). With the surge in popularity of solar power, new design possibilities for its implementation are constantly being considered such as building integrated and rooftop photovoltaic systems (PV) (Malu et al., 2017). Although useful, these designs do not quite meet the demand for solar energy; consequently, solar farms are constructed (Malu et al., 2017). However, if solar PV is to become a competitive renewable energy source, large areas of flat land will be needed; land that is often already in use as farmland (Amaducci et al., 2018). The competition between energy and agriculture for land will be an issue especially here in Massachusetts where land for agriculture is limited. Consequently, there is a need to research agrivoltaic (AV) systems in Massachusetts so that solar energy and food demands can be met in the future. To date, several studies have been performed to examine the potential of AV systems that look at the different densities of panels (by changing spacing between panel rows) within an AV array and device set-ups to optimize both agricultural yields and electricity production. Some studies have also been done to examine the microenvironment effects of AV systems. These studies are summarized below.

### 1.2 Background to Agrivoltaic Systems

Agrivoltaic systems were first proposed in the 1980's as a way to use land for agriculture and energy production by utilizing the land space between solar arrays for agricultural purposes (Dinesh and Pearce, 2016). Eventually, the concept of AV systems evolved to describe systems with elevated solar panels with the land underneath used for agricultural production. Despite the early proposal of AV systems, actual experiments to test the plausibility and efficacy of dual-use systems for energy and agricultural production did not occur until recently. The development, study, and implementation of AV systems is crucial because of the growing world population and demand for food and energy resources. For example, the United Nations Department of Economic and Social Affairs predicts that the world population, which is presently over 7 billion, will grow to about 8.5 billion by 2030 and 9.7 billion by 2050 (UN DESA, 2015). When determining the potential of AV systems, researchers are concerned primarily with how the solar panels impact crop yields by influencing crop resources- mainly the receipt of solar radiation/light (Dupraz et al. 2011). Furthermore, differing levels of solar radiation have been shown to affect microenvironment under the panels--such as soil water and crop temperature (Marrou et al., 2013a). There is even postulation that some of the impacts that panels have on these resources may prove beneficial to crops; for example, if conditions are too hot, the panels may shade the crops and decrease evapotranspiration (Dupraz et al., 2011). However, the reduction of light is considered the main research concern for the production of crops in dual-use systems because plants need light to photosynthesize and grow (Dupraz et al., 2011). Consequently, AV system research must focus on the construction of panel arrays that allow for sufficient light to reach crops. Additionally, plants that are considered shade tolerant, capable of surviving in lower light, may also be of interest in dual-use scenarios (Dupraz et al., 2011).

## 1.3 Set Up of Agrivoltaic Systems

The general set-up for agrivoltaic systems differs from the set-up of traditional ground mounted photovoltaic systems, which are more common because of their lower installation costs and higher panel densities that increase energy production (Santra et al., 2011). In traditional ground-mounted photovoltaic set-ups systems are stationary. The PV panels are positioned about 1.6 feet (0.5-m) off the ground and spacing between rows is minimized to prevent self-shading. There is not spacings between panel clusters within rows since panels abut (Santra et al., 2011). Spacing between panel rows of 5-ft (1.6-m) is generally recognized as the spacing distance that maximizes energy production (Dupraz et al., 2017). The tilt angle of the panels is set to intercept the most solar radiation; this angle is variable and is dependent on specific geographic location (Santra et al., 2017). Although many characteristics remain the same, agrivoltaic systems differ from ground-mounted systems in that the panels are set up several meters above the ground on poles and the distance between rows is usually increased. In some AV systems, the PV panels are constructed to rotate as well. The height of the PV panels effects the distribution of solar radiation at the crop level (Dupraz et al., 2011). For example, when the panels are at a low distance from the ground, they create dense shading whereas as the panel height increases, the spatial distribution of the radiation increases because light is able to penetrate underneath the panels from the sides (Dupraz et al., 2011). Ultimately, the elevated PV panels create conditions where crops are able to grow underneath the panels (Amaducci et al., 2018).

### 1.4 Studies on AV Systems Effect on Crop Yields

The productivity of AV systems specifically crop yields and energy yields are of specific interest. One of the first studies of agrivoltaic systems began in the Spring 2010 at the Montpellier experimental agrivoltaic station in France (Dupraz et al., 2011). In this simulation study by Dupraz et al. (2011), the Land Equivalent Ratio (LER) was used to compare the production of agriculture and solar panel monosystems to two agrivoltaic systems of different panel densities, half and full density. The LER is the sum of agricultural production and electricity production in the AV system versus crop and electricity production separated in monosystems. An LER above 1 means that there is a benefit to the combined system (Dupraz et al., 2011). In the study, a panel row spacing of 5-ft (1.6-m) was used in the full density (FD) AV plot and this spacing is considered optimal for solar energy production while allowing only about 50% of solar radiation to the crop below the panels. The half density (HD) AV plot had 10-ft (3.2-m) between panel rows and allowed more radiation to reach the crop level, about 70%. Panels were mounted 13-ft (4-m) above ground and tilted at an angle of 25 degrees. From the AV plots, light transmission was determined under the HD and FD experiment station panels, and then the STICS (Simulateur multidiscipllinaire les Cultures Standard) crop model (Brisson et al., 1998) was used to predict crop growth in response to different shading and full sun control conditions and environmental conditions at the site. Photovoltaic Software, PVsyst, (Version 6.85, Satigny, Switzerland) was used to find optimal solar panel configuration and then simulate PV production. Durum wheat was the model crop. For the cropping season of the durum wheat, the incident radiation under the panels (available to the crop) was 71% for the HD plot, and for the FD plot there was only 43%

incident radiation. The results of the STICS model show that that durum wheat yields declined in both AV plots compared to yields in the full sun plot. Specifically, for the FD plot, the wheat dry matter declined by 29%, and for the HD plot wheat dry matter declined by only 11%. The LER's in this study using dry matter for wheat yields were 1.19 for the HD plot and 1.43 for the FD plot. Ultimately, the study found that although the FD plot had higher LER's than the HD plot because of higher energy production, the HD plot significantly limited crop yield losses while also maintaining an LER over 1.

In another pioneering study of AV systems by Marrou et al. (2013b), productivity and radiation use efficiency of lettuces, cucumbers, and durum wheat specifically were examined. The experiment took place from July 2010 to Sept 2011 at the Montpellier experimental agrivoltaic station in France as well. The AV experimental plots were the same as the Dupraz et al. (2011) study. Density of panels changed by altering the spacing between rows. The full density (FD) AV plots had 5-ft (1.6-m) between rows, and the half density (HD) AV plots had 10-ft (3.2-m) between rows; so, accordingly, about 50% radiation and 70% radiation were allowed to the crops below in each set-up. The crops planted were cucumber and lettuce (short cycle crops) and durum wheat (long cycle crop). The lettuce was grown in one spring cycle and one summer cycle. The cucumbers were grown for one summer cycle, and durum wheat was grown from November to June. Crops were irrigated in the summer and spring crop cycles and not in the long cycle. The AV systems were located 13-ft (4m) off the ground and at a 25 degree tilt angle. For the lettuces, in the summer, two types were planted: Kiribati and Tourbillon. In the spring, four types, Kiribati, Bassoon, Model and Emocion, were planted. The cucumber was Marketmore variety, and the durum wheat was Claudio variety.

The results showed that the amount of light plants received was about 53% on average in the FD AV plots in summer 2010 and spring whereas in the HD plot the light that crops received ranged from 68% in summer 2010 to 73% in spring 2011. Average dry mass yields of lettuce in the full-sun plot (FS) was 25 g for summer and spring seasons and fresh weight was on average 561 g in summer 2010 and 312 g in spring 2011 for all varieties. In 2010, lettuce yields in the FD plot equaled about 58% of the FS lettuce yields whereas in the HD plot 81% of the FS yields were produced in 2010. In 2011, FD plot yields were 79% of FS plot yields, and the HD plot yields were about 99% of FS yields. So, in 2011 on average spring lettuce yields were barely affected by the shading. It is interesting to note that in 2011, some lettuce varieties in the HD system actually produced higher yields than the FS areas. Furthermore, in the spring all 4 lettuce varieties at harvest had yields that were equal to or higher than what was expected based on the predicted available radiation. This result indicates that light interception improved for the lettuce in shaded conditions. This result is corroborated by evidence that in general, especially in the FD plots, the AV plots tended to have increases in total leaf area per plant (even though there were fewer actual leaves present) compared to the full-sun control plots. Ultimately, the size of the leaves increased in the shade which suggests that AV systems could be further enhanced with the use of more shade-tolerant crops. Marrou et al. (2013b) concluded that in AV systems lettuce yields in the HD plots were affected the least compared to FS lettuce yields and that when considering an AV system to produce crops the system should be designed to allow about 70% radiation to the crops to prevent significant restrictions in yields. Also, he concluded that there are varieties of certain crops that can be chosen for AV systems due to their adaptability to shaded conditions.

In a simulation study of an AV system by Amaducci et al. (2018), a solar tracking AV system, Agrovoltaico, was created and constructed in the Po Valley of northern Italy to determine the effects of the system on rainfed maize. For the construction of the Agrovoltaico system, panels were elevated and attached to a rotating axis and combined with Agrovoltaico software. The Agrovoltaico software combined a radiation model (based on the shading conditions determined from Agrovoltaico system set-up in Italy) with Gecros (a generic crop simulator) (Yin and Van Laarr, 2005) to simulate the growth of maize underneath the tracking panels. Gecros simulates crop yields by modeling photosynthesis and transpiration using climatic factors such as radiation, temperature, wind speed, partial vapor pressure, and available nitrogen and water (Amaducci et al., 2018). The modeled radiation from Agrovoltaico and a climate and environmental dataset of 40 years from the location were input into Gecros. Overall, the software calculates radiation reduction and the effects on simulated crop yields. The study included Agrovoltaico designs that examined different panel densities, one with single density, the second with double density and with each density with panel management fixed (F) or sun- tracking (ST), and compared them to full-sun conditions. There were single-density and double density plots for fixed or sun-tracking panels resulting in 4 experimental plots: F1 (single-density fixed), F2 (double-density fixed), ST1 (single density tracking), ST2 (double- density tracking), and 1 control (full light) plot. The single-density panels had a panel density (panel area/land area ratio) of 0.135, and the double-density panels had a panel density of 0.36. To decrease the density of panels, the spacing between rows of panels was increased. The fixed panels were set at 30 degrees whereas sun-tracking had differing angles throughout the day.

Amaducci et al. (2018) concluded that panel density was more important in influencing radiation than panel management; lower panel density had a greater impact on limiting radiation reduction at the crop level than sun-tracking panels did. For the simulation, average radiation reductions were 14.6%, 12.1%, 31.8%, and 27.9% for ST1, F1, ST2, F2 plots respectively. Overall, the study concluded that, in rainfed conditions, simulated average maize yields over the 40-year simulated period were greater and less variable under the AV plots than in the full-light control conditions. This conclusion is true even though the highest yields were simulated under the full light conditions because the probability that they would occur was below 20% meaning they did not happen often, and the lowest yields were also obtained in the full-light conditions. Overall, there was great variability in the yields simulated for the full light conditions. In contrast, the study found that in the Agrovoltaico plots the chance that simulated maize yields surpassed average yields was 75% compared to only 51% chance in the full-light conditions. It is interesting to note that the benefits and yields of the Agrovoltaico plots increased with drought stressors. Another way to determine the potential benefits of AV systems is by using the LER. In this study, all Agrovoltaico plots exceeded an LER of 1. In general, it was concluded from this study that the maize grown under the AV plots tended to have more stabilized and higher yields in rainfed conditions.

Another dynamic AV study was done by Elamri et al. (2018) and took place at the agrivoltaic experimental station in Montpellier, France. Consequently, the HD and FD plot densities and panel set-up are the same as previous studies for the fixed panels (5-ft

(1.6-m) between panel rows in the FD plot and 10-ft (3.2 m) between panel rows in the HD plot). However, in 2014 two new AV systems were added; a controlled tracking (CT) system and a sun tracking (ST) system. So, there was a control plot in the full sun, fixed plots of HD and FD, controlled-tracking plots (CT), and sun-tracking plots (ST). Both the ST and CT plots had panels that can rotate 50 degrees E and 50 degrees W. The ST and CT plots had the same shading density as the HD fixed device plot and were located 16.5-ft (5-m) above ground. The ST plot panels were designed to follow the sun to maximize the interception of light and, consequently, to obtain max electricity from the panels. In contrast, the CT plot panels were designed to limit interception of light in the morning (be in a vertical position), shade crops during the hottest hours of the day (in the horizontal down position), and then later in the day reduce interception again by returning to a vertical position. The study used Madelona romaine lettuce planted in spring and summer cropping cycles in 2016 and examined the effects of the different shading condition of the AV plots on the lettuce yields at harvest.

Results showed a decrease in daily radiation of -33% for the ST plot, -30% for the HD plot, -49% for the FD plot, and -23% for the CT plot. Four harvest dates were used to obtain data on biomass of the lettuce: 2 of the dates in spring 2016 and 2 in the summer 2016. For the spring harvests of lettuce, there was a significant decline in biomass for the AV lettuce plots when compared to the control plot but no significant difference in the yields between AV plots ST, CT, or HD. For example, in the first spring harvest the full sun control plot produced a lettuce average fresh weight of 454 g whereas the fresh weights of lettuce in the AV plots were about 24% less on average. For the summer harvests, there were differences between the AV plots and the full sun control plot with the full sun control plot producing the highest yields, but it was also found that the ST plot produced significantly higher biomass than did the CT or HD plots for the first summer harvest. For the second summer harvest the full-sun control plot produced the largest biomass yield, and the AV plots produced less with the HD plot producing significantly less than the ST or CT plots. For the spring harvest, LERs for the ST plot =1.27, for the CT plot=1.07, for the HD plot =1.28, and for the full sun control plot=1. For the Summer, LER for the ST plot =1.36, for the CT plot=1.09, for the HD plot= 1.19, and for full sun control plot=1. Elamri et al., (2018) concluded that given the small influence of shading on crop growth and the LER values, the ST AV system is the most effective design followed by the fixed HD AV system.

In the next experiment by Valle et al. (2017), the same dynamic system at the Montpelier agrivoltaic experiment station was used as in the Elamri et al. (2018) study. Two lettuce varieties, Kiribati and Madelona, were planted in fall 2014, spring 2015, and summer 2015. The HD and ST plots had Kiribati and Madelona planted in fall, spring, and summer whereas the CT plot had Madelona and Kiribati planted in only spring and summer (Valle et al., 2017). It was determined that in all AV plots in all seasons that daily rsolar adiation transmission was lower than in the full sun plot. The CT plot had higher transmitted radiation than the ST or HD plots over all three seasons, 30% more compared to the ST plot and 40% more compared to the HD plot. In the spring and summer, CT plot devices transmitted the most radiation, ST plot devices the second most, and the HD fixed panels plot the lowest. In the fall, ST plot devices transmitted more radiation than the HD plot fixed panels, and there was no CT plot experiment in fall. For crop yields, lettuce dry mass was lower in all the AV plots than in the full-sun plots in the spring or summer. When looking at effects of season, cropping in the fall decreased the effects of the AV plot shading on crop yields quite dramatically. Furthermore, it was noted that the Kiribati lettuce variety was more resilient to reduction in light than the Madelona variety. Consequently, in the fall, dry mass of the Madelona lettuce was only 18% lower in the HD or ST plots when compared to dry mass yields of the full-sun control plot whereas no significant difference occurred between yields of Kiribati lettuce in the full-sun plot versus the AV plots. A 13-15% increase in dry yields of lettuce was found in the ST plot compared to the HD plot in the spring or summer for Madelona lettuce. For the CT system in the spring, yields of lettuce were higher than in either the ST or HD plots, but in the summer, they were similar to the CT plot for both lettuce types. Additionally, like the Marrou et al. (2013b) study, Valle et al. (2017) determined that there was evidence for lettuce adaptation to shaded conditions because in all AV plots, the leaf number of lettuces tended to decline, but their actual leaf area increased. When comparing the plots and their PV production, it was determined that compared against the fixed HD plot, on sunny days the ST plot had increased energy production by 74% whereas the CT plot had decreased energy production by -23%. On cloudy days PV production was lower in all AV plots than it was on sunny days. When looking at cloudy days, the ST plot device still outperformed HD plot panels in energy production and this time so did the CT plot device because its angle, even during a short period of time, captured more radiation than the HD plot device. In all AV plots, the LER value was above 1 meaning the AV system of crops plus electricity production was more efficient than their respective monosystem production. With LER's of 1.5 and above, the ST plot proved the most effective system to optimize AV outputs; the high LER in the ST plot can be attributed mostly to PV production. It is important to note that the CT plot was the most efficient in producing biomass. Consequently, LER for either CT or ST plots were higher than the HD plot.

Overall these studies show that AV systems, with spacing between rows that allow for higher levels of radiation, about 70% radiation, to the crops, can optimize crop yields/growth in AV systems. Moreover, they demonstrate, using the LER, that the combined use of land for agriculture and solar energy production is more productive than separating agriculture and solar energy production so research into these systems is important. Furthermore, the studies indicate that in dynamic systems, a sun-tracking device is more efficient than a controlled device at maximizing AV outputs although CT devices produce higher crop biomass. Lastly, certain studies indicate that particular crops and crop varieties, such as lettuce, can be specifically chosen for AV systems because of their adaptability to shaded conditions-to further optimize AV system outputs.

### 1.5 Studies on AV Systems Effect on Microenvironment

As mentioned previously, to determine the impacts or benefits of agrivoltaic systems a researcher's main interest is in how solar panels impact overall crop yields by influencing solar radiation; however, they are also concerned with how shading and different levels of radiation affect the microenvironment under the panels in agrivoltaic systems. This concern is because aspects of the microenvironment like temperature and soil water can affect photosynthesis. For example, if shading affects soil water dynamics or the temperature of crops or soils. For the concern of this literature review and thesis we will examine mainly crop temperature and soil water content as affected by a reduction in solar radiation and. Differing levels of radiation have been shown to affect microenvironment, such as soil water content and crop temperature (Marrou et al., 2013c). For example, soil water can be affected by panel shade by affecting evapotranspiration rates (Marrou et al., 2013 c) or by distribution of rain as a consequence of panels (Armstrong et al., 2016).

A study by Marrou et al. (2013a) examined whether crop growth is affected by microenvironment changes attributed to photovoltaic panel shading. The experiment took place from July 2010 to Sept 2011 at the Montpellier experimental agrivoltaic station in France as well. The AV experimental plots were the same as the Dupraz et al. (2011) study. Density of panels changed by altering the spacing between rows. The full-density (FD) AV plots had 5-ft (1.6-m) between rows, and the half-density (HD) AV plots had 10-ft (3.2-m) between rows; so, accordingly, about 50% radiation and 70% radiation were allowed to the crops below in each set-up. The crops planted were cucumber and lettuce (short cycle crops) and durum wheat (long cycle). The lettuce was grown in one spring cycle and one summer cycle. The cucumbers were grown for one summer cycle, and durum wheat was grown from November to June. Crops were irrigated in the summer and spring crop cycles and not in the long cycle. The AV systems were located 13-ft (4-m) off the ground and at a 25 degree tilt angle. For the lettuces, in the summer, two types were planted: Kiribati and Tourbillon.  In the spring, Kiribati, Bassoon, Model and Emocion types were planted. The cucumbers were Marketmore variety, and the durum wheat was Claudio variety. Measurements were taken for incident radiation that reached the crops and for crop temperature.

Results showed that below the panels incident radiation was 32% for the FD plot and 48% for the HD plot for the spring cycle; 37% for the FD plot and 62% for the HD plot for the summer crop cycle; and 52% for the FD plot and 68% for the HD plot for the long cycle. Daily crop temperatures were impacted by panel shading as well. For example, wheat crop temperature increased at night in the AV plots by about 2 degrees Celsius. In contrast, FD and HD plot wheat crop temperatures were lower than the FS control plot by about 3 degrees Celsius during the daytime hours. Marrou et al. (2013a) concluded that, in general, the crop temperatures in the shade of the panels were generally lower than in the FS conditions during the day and at least for the wheat and the lettuce they increased significantly at night. Overall, crop temperatures in the full sun versus under the panels in the AV plots differed during the day and night; in AV plots, mean daytimes temperatures were lower, and mean nighttime temperatures were higher than in the full sun plots. However, despite these differences mean daily crop temperatures were quite similar between AV and FS conditions overall because the differences tended to even out over the course of the day.

In another paper from the 2010 and 2011 study in Montpelier, France, Marrou et al. (2013c) specifically studied and calculated the evapotranspiration of drip-irrigated crops lettuce and cucumber in the summer of 2011 from March-August under three different shading intensities: Full sun, FD, and HD (same set-up as previous studies). Crops were irrigated, and the total rainwater inputs were determined from the weather station. Although it may be expected that due to the PV paneling and water runoff that water inputs may vary in the experimental AV plots from the full sun plot, the total amount of water in the full sun, HD, and FD plots was considered to be equivalent because there is no drainage of the water occurring. Microenvironment variables, soil water content and water potential, were measured. Actual evapotranspiration (AET) was calculated with a water balance equation and soil water measurements in each treatment. For lettuce in FD plots, the AET was 76% of the full-sun plots. For lettuce in the HD plot, AET was 78% of the full-sun AET. For cucumber AET also was reduced compared to the full sun; in FD plots AET was 71% of the full-sun AET, and in the HD plots AET was 86% of the full-sun AET. From the study it was concluded that under solar panels evapotranspiration is reduced (so water loss is reduced). Marrou et al.  (2013c) attributed the reduced evapotranspiration to the reduction in light because as light decreases so does heat under the panels. Overall shading in the AV systems saved between 14-29% water depending on the level of shade (FD or HD).

Similarly, an Adeh et al. (2018) study looked at changes to the microenvironment, specifically soil water content, of an AV system using non-irrigated pasture below solar panels. The solar arrays were located on the Oregon State Campus (Corvallis, Oregon, U.S.A.) and made up a 6-acre AV system. The study took place from May-August 2015. The panels were installed 3.5-ft (1.1-m) above ground in continuous rows inclined in a southern direction at 18 degrees. The distance between panel rows was 20-ft (6-m). The study examined three areas around the panels. The first area was the sky full open (SFO) site located in the middle of the 6-m between rows to the bottom of the next row of panels; it got full sun. The second area was the solar partially open (SPO) site located from the top of the panel 3-m into the 6-m in between; it received partial shade. The third area was the area directly below the panel that received no sun, a fully covered area (SFC). There was a full-sun control as well located outside of the array. Soil water measurements were taken at 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 m depths for each treatment (SFO, SPO, and SFC) and for the control. Soil water content declined faster in the sky full open area than in the SPO or SFC area and the control; while the SFC area had the highest soil water content followed by SPO, and SFO. The areas under solar panels maintained higher soil water content during the study period.

In the dynamic systems studies mentioned previously that examined biomass yields in agrivoltaic systems, some of them also looked at elements of the microenvironment and how they were affected by solar panels. For example, the Amaducci et al. (2018) study additionally used the agrivoltaico software and climate dataset to model soil evaporation and transpiration and soil temperature to find that the panels influenced the microclimate under the panels.  Evapotranspiration was lower under the panels than in full light; the average evapotranspiration under panels was 442 mm and 477 mm in the full sun control per year. The Elamri et al. (2018) dynamic study additionally estimated soil water content at 5, 15, and 25 cm depths for each plot. Elamri et al. (2018) observed a larger water consumption in in the full sun plot than in AV plots based on lower estimated daily evapotranspiration rates in the AV plots (-22% in ST, -26% in HD, and -19% in CT). Lastly, Valle et al. (2017) dynamic study also measured leaf temperature and found that when examining leaf temperature of lettuces, instantaneous differences in leaf temperature between the full sun and shaded AV plots were found but when averaged over the course of an entire day the leaf temperatures were actually quite similar in the full sun  plot and AV plots. Specifically, on cloudy days these temperature differences were minimal and only very slight on sunny days anyways.

What has not been addressed in literature concerning AV systems so far is gap spacing distance between panel clusters within a row and how the distance can be varied to optimize AV systems.

## 1.6 Shading Effect on Nutrients in AV Systems

In agriculture, the three main macronutrients needed in plants are nitrogen, phosphorus and potassium, so it is important to understand their levels in AV systems and how shade caused by the solar panels influences them. Shading can have an effect on these nutrients because N P and K are macronutrients necessary for crop growth, and variation in sunlight has been shown to effect their levels (Blair et al., 1983, Burridge et al., 1964, Diaz-Perez, 2013, Gent, 2008, Liu et al., 2003). As of yet nutrient levels of crops grown underneath panels in agrivoltaic systems have not been studied. However, there are studies regarding the effect of shading in general on N P and K in crops. Burridge et al. (1964) found that in cacao (*Theobroma cacao*) that shade affected nutrient levels by increasing the levels of N P and K with increased shade treatments. Blair et al. (2013) found that in flowering dogwood (*Cornus florida*) a small deciduous tree, yaupon (*Ilex vomitoria*) an evergreen shrub, and Japanese honeysuckle (*Lonicer japonica*) grown with shade levels of 0, 55%, and 92% that P levels in leaves increased significantly with 92% shade (Blair et al., 2013). Diaz-Perez (2013) farm study on bell peppers (*Capsicum annum* L.) grown with different shade levels (0, 30%, 47%, 62%, 80%) found that shading may have allowed for pepper yields to not be reduced because shading modified the temperature so nutrient uptake was increased (Diaz-Perez, 2013). Similarly, a Liu et al., 2003 study on tomatoes (*Lycopersicon esculentum Mill. cv. Maofen*) grown at three shading levels (0, 40, and 75% shade), shows N P and K levels were unaffected by shading in the early flowering and peak flowering stage but for the late flowering stage with shading of 40% and 75%, N P and K concentrations were increased (Liu et al., 2003). There was no difference in N and K between 40% and 75% while P was different between the shading treatments (Liu et al., 2003). In another study by Gent (2008) that examined tomatoes (*Lycopersicon esculentum Mill. cv. Maofen*) grown in greenhouses with different levels of shade; 15, 30, 50% shade level or full sun, it was found that shade increased N P and K concentrations in the tomato leaves.

Nitrogen is required by plants in large amounts; for example, corn dry mass is about 3% N whereas tomato dry mass is about 4% N (Hue and Silva, 2000). N deficiency symptoms include stunted plant growth and yellowing of leaves because N is an essential component in chlorophyll and protein so there is less green color if N is deficient (Hue and Silva, 2000). Ultimately, N deficiency leads to decreased photosynthesis and crop yield.

Phosphorus is also a major requirement in plants, but, in lesser quantities than N and its deficiency also limits crop growth and yields (Hue and Silva, 2000). This deficiency occurs because P is an essential component of DNA and RNA and consequently, is necessary for growth and reproduction in plants (Hue and Silva, 2000). Crops that lack P have stunted growth and underdeveloped root systems and stems, malformation of seeds and fruits, and often develop a purple color due to accumulations of anthocyanins (Hue and Silva, 2000). Most plants require from 0.2-0.5% P by dry weight in leaves (Hue and Silva, 2000).

Potassium is necessary in quite large amounts in plants because it maintains the water content in plant cells to keep plants turgid, regulates osmotic potential, controls stomatal activity, and is involved in water uptake, water retention, and water transport (Hue and Silva, 2000). Plants with K deficiency are less resistant to disease and have stunted and shriveled fruits and seeds (Hue and Silva, 2000). K deficiency usually manifests on the outer edge of leaves as small white or yellows spots which turn brown, and the leaf dies from the edge. K levels in vegetables such as cabbage leaves are 4.5-7.5% and lettuce 4-7.5% (Hue and Silva, 2000). Ultimately, because this experiment is examining whether solar panels (shading) affects crops yields, N P and K nutrient concentrations are of interest because N P and K are macronutrients essential to plant growth.

**1.7 Conclusion**

With a growing population and expanding industry alternative sources of energy and food production must be found. AV systems have the potential to meet both of these demands. AV systems have been studied by altering the spacing between panel rows and also by using technologies that allows for solar panel position to change throughout the day to allow more solar radiation to be collected by the crops below. What these studies have concluded so far is that panel density in the systems should be spaced to allow 70% solar radiation to the crops and that for the tracking panels it is best to use sun tracking versus controlled tracking panels (sun tracking panels track and move with the angle of the sun throughout the day while controlled tracking panels are vertical until sunniest part of the day) because sun tracking panels produce more total energy for the system while controlled tracking only produce more biomass.

For the studies that examined the microenvironment in AV systems, soil water content was lower below panels because of reduced evapotranspiration. Similarly, leaf temperature of crops was generally lower under the panels during the day especially on sunny days, but these differences might average out when looking at daily average temperatures because they were higher at night. Finally, nutrient levels, specifically, N P and K, were higher in crops that were grown in shaded conditions than in crops grown in full-sun conditions. What has yet to be addressed in these AV system studies is gap spacing distance between panel clusters within rows and how the distance can be varied to optimize AV systems by increasing crop yields instead of just altering the distance between panel rows. Furthermore, how these gap distances would affect crop temperature and soil water content and nutrient levels has not been examined. Additionally, there have not been studies to show the potential of the systems in an area such as western Massachusetts.

# CHAPTER 2

# THE EFFECT OF GAP SPACING BETWEEN SOLAR PANELS ON CROP BIOMASS YIELDS, NUTRIENTS, AND THE MICROENVIRONMENT IN A DUAL-USE AGRIVOLTAIC SYSTEM

## 2.1 Introduction

Energy demands and human population are increasing with some predictions estimating that the global energy demand will double by 2050 as a consequence of population and economic growth (Adeh et al., 2018). Furthermore, the population is predicted to reach 9.8 billion by the mid-century and 11.2 billion by 2100 (UN DESA, 2015) and will increase the demand for food. Solar power is one of the most promising sources of renewable energy because of its abundance and the costs associated with it have fallen approximately 10% in the past thirty years (Adeh et al., 2018). However, the land requirement of solar installations has become a concern because it competes with agriculture for large amounts of agricultural land (Amaducci et al., 2018). Agrivoltaic systems are systems with elevated solar panels positioned over crops so that land can be used for agriculture and energy production and have the potential to address food security and renewable energy concerns. The construction of these systems and how they allow solar radiation to reach the crop are crucial to their success.

The Dupraz et al. (2011) study of durum wheat is credited with the introduction of AV systems. This study determined that AV systems that allowed 70% light to crops yield 89% of full sun crop biomass. Marrou et al. (2013b) similarly found studying lettuce varieties that when considering an AV system to produce crops, the system should be designed to allow about 70% radiation to the crops to prevent significant limitations in biomass yields. Marrou et al. (2013b) also concluded that there are certain lettuce varieties that can be chosen for AV systems due to their tolerance to shaded conditions. Studies of AV systems also have shown that changes in solar radiation caused by paneling affects the microenvironment underneath. For example, Adeh et al. (2018), Marrou et al. (2013c), and Amaducci et al. (2018) reported that evapotranspiration decreased in AV plots compared to full-sun plots. While, Adeh et al. (2018) and Marrou et al. (2013a) found that panels may affect crop temperature below them. Specifically, Marrou (2013a) found that under panels during the day temperatures of crops decrease compared to full sun crop temperatures but are higher at night under panels (Marrou 2013a). Additionally, multiple studies that have been performed including Burridge et al. (1965), Blair et al. (1983), Diaz-Perez (2013), Gent (2008), and Liu et al.( 2003), indicate that increased levels of shading may cause an increase in nutrient (N, P, K) levels in the leaves of crops. What has not been addressed in literature concerning AV systems so far is gap distance between panel clusters within the AV row arrays and how they can be varied and used to optimize AV systems by increasing crop yields. Furthermore, how these varying gap distances between solar panels will affect crop temperature and soil water and nutrient levels is not clear. Moreover, no studies have been published on AV systems in the Northeastern U.S.A.

In New England, specifically Massachusetts, farmland is a limited and decreasing resource due to an array of factors that include a high population density, limited suitable land, and high land prices so AV systems would be beneficial here (MDAR, 2015). As the use of PV expands, solar farms are becoming increasingly common. Moreover, due to limited revenue potential and high operating costs of farming, the sale of farmland to solar developers is quite enticing for struggling farmers. In response, in an attempt to keep their farms, farmers have become interested in the possibility of installing AV systems to increase their profits or to offset operating costs and provide a clean renewable energy source, but only if the costs of implementation are not too high. Additionally, as the need for alternative energy increases, solar power has emerged as one of the most promising forms of renewable energy for Massachusetts. Consequently, AV systems have potential in Massachusetts to help save farmland and act as a source of renewable clean energy as current research shows that agrivoltaic systems can be quite effective at producing both crops and solar energy.

However, it is important to note that although investing in solar energy on their farms may be of benefit to farmers in the long-term, at the moment it is still a financial burden to install solar panels on farms especially for farmers already experiencing financial hardship. Consequently, for AV systems to succeed, it is necessary that programs and incentives offset the cost of initial AV system/PV installation for farmers because of the long payback on investment that solar panels have and that more research is performed. The Massachusetts Department of Energy Resources recently created the Solar Massachusetts Renewable Target (SMART) Program. This program creates incentives to help increase the use and implementation of solar energy in Massachusetts (Dowling, 2018). The incentives are tax based (Dowling, 2018). Of particular interest here, is the Agricultural Solar Tariff Generation Unit (ASTGU) part of the SMART program because it allows for facilities that meet the dual use requirements of the ASTGU to apply for additional compensation in addition to the credit received for solar use that is not dual use (Dowling, 2018).

This research specifically continues the Photovoltaic Dual-Use Research Project going on at the UMass South Deerfield Crop Research Farm led by Dr. Stephen Herbert that is examining crop yields of vegetables (Swiss chard, kale, peppers, and broccoli) grown under solar panels with different gap distances between panel clusters within panel rows. It further begins to examine the effects of shade treatments (gap distance between panels) on nutrient levels of crops, crop temperatures, and soil water content. This project is necessary to help prove, as in the above studies, that agricultural land can be kept producing food at the same time as it produces a clean and renewable energy source and that solar panels can help offset costs of farm operations. This research is particularly important in that it will increase knowledge on the potential to grow crops underneath solar panels as previous studies have done but also examines the gap distance between panel clusters within a row and how this gap distance variation affects light levels to the crops underneath the panel and to either side of it and the consequent crop yields. Moreover, the research will evaluate the AV system potential here in Massachusetts and this method of varying gap distances between panel clusters within rows in AV systems has not been covered in the research of AV systems so far. Current research has examined mostly altering panel density through varying spaces between solar panel rows--not by altering panel density through differing gap distances between panel clusters within rows. Also, there have not really been any published studies in this location as of yet.

The project began in 2010 when an AV array consisting of two panel rows (north and south positioned replicates) were installed on land at the UMass Crop Research Farm in South Deerfield (Herbert, 2018). The panels are installed in an open and unobstructed field with the panels facing the south direction. In this experiment there are a total of 106 solar panels organized into clusters of 3 panels on a cross beam supported by poles in two rows of panels at a height of 7.5-ft (2.3-m) from the ground. The panels are installed with different gap spacing distances between the clusters of panels within the rows. Originally, they were used to examine the effects of differing gap distances between panel clusters on pasture growth to find optimal construction techniques for such systems. The differing gap distances are 2-ft (0.61-m), 3-ft (0.91m), 4-ft (1.22-m), and 5-ft (1.52-m). The panels are installed on poles without concrete bases to allow for unimpeded crop growth. Each row (replicate) contains 4 plots consisting of a panel cluster and each of these gap distances on either side of the panel cluster but in a randomized block design. Each of these plots (with its varying gap distance between panel clusters) will be referred to as an AV plot because they are located in the AV system. In each row there is also a full sun plot located in front of each panel row so it receives no shading from the solar panels. There is enough spacing between the north and south positioned panel row replicates to prevent self-shading. During the earlier experiments, the pasture underneath the panels was rotationally grazed by cattle. Dry matter of the pasture below the panels was measured before it was grazed. Results of these early experiments showed that 3.5 to 4-ft gap distances between panel clusters produced yields of pasture that were 90% of full sun yields and gap distances between panels of 4 to 5-ft produced yields of 95% of full sun yields.

In this experiment, we hypothesize based on previous research results on AV systems and results from this specific project so far that by creating different gap distances between panel clusters within rows of 2-ft, 3-ft, 4-ft, or 5-ft at the Photovoltaic

Dual-Use Research Project Station an optimal gap distance between panel clusters for AV systems that maximizes crop growth under panels can be found. Furthermore, the research will introduce and validate a new AV design scenario that allows more light to be transmitted to the crops below by reducing panel density within panel rows of an AV system. Based on previous research at the site we expect that the optimal gap distance between panels will lie between 4 and 5-feet. We also predict that the control full sun plot will have the highest crop yields. Moreover, we believe that for area within plots (spacing to the left of the panel, middle—under the panel, and spacing to the right of the panel) crop yields will not vary because of the changing angle of the sun. The changing sun angle will allow sunlight to penetrate the gaps between panels to reach below the solar panels so that all areas receive similar sun throughout the day. The area within plots was added as a variable to increase the degrees of freedom in the experiment. This study will also examine nutrient levels for each experimental AV plot against the control plot nutrient levels to see how they vary with shading and also soil water and leaf temperature. We expect that for N P and K nutrient concentration levels will increase with shade, that for leaf temperature during the day there will be variation between the full sun plots and under the panels in the AV plots because of direct solar radiation but that may vary if the conditions are not sunny, and finally that soil water content will increase with shade because of the reduction in radiation and warming under the panels.

***Hypotheses are:***

- Crop yields per plant will be highest in full-sun conditions.
- Crop yields per plant in the AV (with gap distances between panel clusters) plots with 4-5-feet gap distances will not be significantly reduced compared to yields in the full sun plots.

- The specific position of the crop within plots (to the left of panel, under the panel/middle, and to the right of panel) will not affect yields because of the sun movement throughout the day so all crops receive similar light.
- N P and K nutrient levels will increase in samples with increases in shade (smaller gap distances between panels).
- Soil water will increase with shade (smaller gap distances between panels).
- Leaf temperature will be higher in full sun plots than under the panels and will vary with cloudiness.

**2.2 Material and Methods**

One main experiment is conducted on Swiss chard, kale, peppers, and broccoli to examine the effect that different levels of shading due to AV paneling have on crop yields and nutrient levels. Firstly, there are two rows of solar panels (north and south rows) that served as replicates. Each row has solar panel clusters with either 2-ft, 3-ft, 4-ft, or 5-ft gap distances to the right and left of a panel cluster. The area below each panel cluster plus its gap area to the left and right served as an experimental AV plot because gap distance is the variable of interest in this experiment. In each north and south panel replicate there is also a full-sun control plot located in front of the row. Together the AV plots and the control plots will be referred to as the experimental plots. The AV plots are in a randomized block design in each row so in each panel row the gap distances are in different orders. Crop yields are determined for each AV plot and for each area within plot (Left, Right, Middle) within it and compared against control plot yields with no panel overhead. Left, Right, and Middle of the experimental plots are measured as an additional treatment within the experimental plots to increase the degrees of freedom. Then, N P and K are analyzed for each experimental plot and its areas within.

Additionally, some aspects of the microenvironment are monitored to get an idea of how they change with shade; these included light percentage of full sun at the crop level, leaf temperature of the pepper leaves, and soil water content.

### 2.2.1 Light Measurement

To establish the degree of shading or reduction in solar radiation caused by the solar panels in the AV plots light measurements were taken prior to harvest. They were taken on June 21st 2018 at noon with the sun directly overhead. Because the light measurements were only taken at one time, noon, it was when the middle area directly under the panels was being shaded. It is important to note that different areas (L, R, M) within the AV plots under the panels will receive varying amounts of light depending on the time of the day due to changes in the sun's position throughout the day but over the course of the day all areas should receive similar amounts of light. The light measurement is taken to establish how much radiation is reduced in the shade of the panels and that solar radiation is reduced overall in the AV plots compared to the full sun plots. Light measurements were taken using Li-188B Integrating Quantum/Radiometer/Photometer (LI-COR Lincoln, Nebraska) and results were recorded in photosynthetic photon flux density (ppfd). Light measurements were taken at the crop level in each of the experimental plots and area within it (3 measurements for each area were taken and then averaged).

**Equation 2.1 Calculation for Light Percent of Full Sun**

[Light Percent of Full Sun] in AV plot = (Instrument reading in AV plot (ppfd)/Instrument reading in full sun (ppfd)) x 100 x (gap spacing in AV plot (ft)/width of panel (5.5 ft))

### 2.2.2 Crop selection

The crops were selected based on what is commonly grown in Massachusetts. Specifically, leafy vegetables Swiss chard and kale were selected because leafy vegetables are considered shade tolerant which is generally because of their high leaf surface area to intercept light (Seidlova et al., 2008). Peppers and broccoli, flowering vegetables, were chosen as locally grown vegetables that are not shade-tolerant. Broccoli (*Brassica oleracea var. italica*) was purchased from Plainville Farm, Hadley MA, and Lady Bell Peppers (*Capsicum annuum*), Curly Kale (*Brassica oleracea var. sabellica*), and Bright Lights Swiss Chard (*Beta vulgaris var. cicla*) were bought from Harvest Farm, Whately, Massachusetts and transplanted to the AV Photovoltaic Dual-Use Research Project Plot set up at the UMass Crop Research Farm in South Deerfield, Massachusetts. The soil type is Winooski silt loam.

### 2.2.3 Experimental Design/Set-up

**Figure 2.1: The AV Photovoltaic Dual-Use Research Project set-up at the UMass Crop Research Farm in South Deerfield, Massachusetts.**

The experiment was completed at the existing AV Photovoltaic Dual-Use Research Project set-up at the UMass Crop Research Farm in South Deerfield, Massachusetts. This set-up consists of 106 solar panels arranged in panel clusters on poles (3 panels per cluster with panels arranged horizontally) with varying gap distances between them in two replicate rows. The 106 solar panels are rated to produce 16.8 kW of renewable energy on 0.14 acres. There is enough spacing between the north and south panel rows so that there is nothing to obstruct sunlight. The panels are installed in an open field and faced southward. The panel clusters are mounted on poles at 7.5-ft high without concrete bases. Specifically, the gap distance between the panel clusters is varied so that in each row there is AV plots with either 2-ft, 3-ft, 4-ft, or 5-ft feet gap distances to each side of the panel cluster. For the purpose of this experiment, a panel cluster with the varied spacing to each side will be referred to as experimental AV plots.

Within the two rows of panels (north and south positioned panel replicates) the AV plots (with different gap distances) are randomized in their placement. In front of each north and south panel row there are full-sun experimental control plots. Additionally, in the experimental plots, area within plot (to the left or right of the panel or the middle-under the panel) is a variable as well but no effect is expected by area within plot for crop biomass yields and nutrient concentrations; area was added as a variable to increase the degrees of freedom in the experiment. However, there is a difference expected by area within plot for the light measurement because it was only taken at one time of day when the middle area was being shaded; so, the middle area light measurement will be lower than the L or R in this instance. However, if light measurements were to be taken at different times of day the L or R areas could be lower in light than the Middle and the amount of light received at the crop level in each area should be similar over the course of a day. The light measurement, however, is just done to illustrate that the shading in the AV system caused light reduction to the crops when compared to full sun plots. Additionally, it is possible that area variable may have an impact on soil water content.

An electric fence 40 inches high (Premier Pig QuikFence (Washington, Iowa)) is set up to enclose the north and south panels rows and the growing area underneath them to prevent animals from eating the crops. In each north and south solar panel row four PV drip irrigation pipes (TORO ¼ inch Blue Stripe Drip Tubing (Bloomington, MN)) are run in parallel rows underneath the panel area along the soil surface, and 1 pipe is installed in the full-sun plot in front of the panel row. Crops are irrigated throughout each week to maintain adequate soil water. Weed block (RSI Polypropylene All Weather Landscaping Ground (Dover, NJ)) is laid under the panel growing area above the irrigation tubes. Holes are cut in the weed block every 12 inches for planting in the 4 parallel rows under the panels and in the 1 control row in front of the panels. Holes are 3x3 inches. Holes are also cut to allow for the panel poles, and the weed block is held down with wire stakes. Fence and pipes were checked weekly for animal intrusion and leaks etc.

In each north and south row replicate the crops are planted in the 4 parallel rows under the panels and in the control areas in front of the panels and span the length of the rows. On May 21$^{st}$, 2018 broccoli, kale, and Swiss chard were planted, and on May 23$^{rd}$ the peppers were planted. On June 12$^{th}$ broccoli had to be replanted because it flowered too early (bolted). Blue and pink flags are used to mark the areas of harvest under each area within the plot (L, M, R). Specifically, the pepper plants are tied with colored ribbon so that the fruit is collected from the same plants at each harvest because there are multiple harvests for peppers. Fertilizers were applied three times in 8 oz doses to each plant. Fertilizer is made with 5 tablespoons of Peters Professional Hydroponic Special Fertilizer (a 5-11-26 fertilizer) and 5 tablespoons of Calcium Nitrate dissolved in 10 gallons of water on June 9$^{th}$, 16$^{th}$, and 30$^{th}$ 2018. The fertilizer solution was remade in the 10 gallon stock solutions until all the plants received their measured out 8 ounces (done with a cup).

### 2.2.4 Harvest Fresh and Dry Weights and Fruit/Leaf Number Per Plant

For each measurement, 30 samples are taken: 3 (one for each area L, M, R) in each experimental plot in each row at harvest. At harvest, plants are cut below the fruit or leaf. Leaves and fruits are counted, and then for each experimental plot area they are transferred to paper bags and weighed. Plants are then dried in a forced-draft oven at (70 degrees C) until they are dry. Then their dry weights are obtained. For kale and Swiss chard, leaves are counted if they are over 3 or 4 inches and alive. Pepper fruits are counted above 3 or 4 inches in length as well. At harvest, the total plants for each section collectively are weighed and counted.

#### 2.2.4.1 Swiss Chard Harvest

All plots of Swiss chard were harvested on July 18, 2018. At harvest, number of plants (how many holes/spaces they were collected from), actual plant number (if more than 1 plant per hole), leaf number (over about 3 inches in length) and leaf (blade + petiole) fresh weights are collected. The leaves are then dried to obtain dry weights.

#### 2.2.4.2 Kale Harvest

Kale was harvested on two different dates because the control plot matured before the AV experimental plots. We were looking at overall crops yields for the season, so this does not matter. The full sun control plots of kale were harvested on July 24, 2018 and the AV plots were harvested on August 2, 2018. At harvest, the number of plants (how many holes/spaces they were collected from), the actual plant number (if more than 1 plant per hole), leaf number (over 3 inches in length) and leaf (blade + petiole) fresh weight are measured to determine yields. The leaves are then dried and measured to obtain the dry weight of Kale.

#### 2.2.4.3 Pepper Harvest

As mentioned before, to harvest the peppers in each experimental plot from the same plants each time, the L, R, and M areas are marked with different colored tape. Overall there were 8 pepper harvests in this experiment. When harvested only the mature peppers are harvested from each section (if there are any present). Harvest dates occurred on July 19$^{th}$ and 25$^{th}$, August 6$^{th}$, 20$^{th}$, and 28$^{th}$, September 7$^{th}$ and 19$^{th}$, and October 5$^{th}$ 2018. At harvest, the number of plants are counted for each section (same plants each harvest because plants were tagged), fruit number, and fruit fresh weight. The peppers are then dried, and their dry weight is obtained. The data from all 8 harvests is summed to get total yield per plant per plot.

#### 2.2.4.4 Broccoli Harvest

All plots of broccoli were harvested on August 13, 2018. At harvest number of plants, stem (blade + petiole) fresh weight, flower head fresh weight, flower head number are measured or determined. The flower heads and stems are then dried to determine broccoli dry weights.

### 2.2.5 Phosphorus and Potassium Concentrations

After the plants (Swiss chard, kale, pepper, and broccoli) are dried, they are ground using a Wiley Mill.  A 0.2-g sample of ground plant material is weighed into a lidded high-form porcelain crucible. The samples are then placed in a muffle furnace at 500°C and combusted for 6 hours. After 6 hours, the furnace is turned off, and the samples are cooled. Next, 15 ml of 10% HCL is pipetted into each sample to dissolve the ash and stirred with a Teflon stir rod. Each sample is then filtered with 11-cm Whatman #2 paper into 15-ml scintillation vials.

Phosphorus and potassium are measured with a Microwave Plasma-Atomic Emission Spectrometer (MP-AES 4200 Spectrometer, Agilent Technologies, Santa Clara, CA).  Separate standards are made for P and K because of high K levels in the crops. However, the stock solution used is the same. 4.394 g of $KH_2PO_4$ in water + 10 ml of

HCl (to make a liter) resulting in a 1,000 ppm P and 1260 ppm K solution. The P measurements standards are made containing 0, 50,100, 150, 200, and 250 ppm P. For K, plant tissue analysis standards were made containing 0, 250, 315, 380, 440, 505, 570 ppm K. Firstly, the $KH_2PO_4$ is added to each 100 ml volumetric flask, then deionized-distilled water is added, then 10ml of 10% HCl are added to each sample to match the HCL added to dissolve the ash. The standards are created to have a similar matrix to the crop samples being tested. The standards are formulated so that a calibration curve could be made on the spectrometer before the samples are run. The standards are rerun every 30 samples to check that the MP-AES is calibrated. Additionally, a leaf sample with known P and K concentrations is measured as well to check for accuracy of the readings. An auto-sampler is used.

**Table 2.1 Phosphorus Standard Formulation for use in Spectrometer**

| Phosphorus Standard ppm | Volume of .41% $KH_2PO_4$ ml | Volume of 10% HCl ml | Volume of Deionized distilled $H_2O$ ml | Final volume of standard ml |
|---|---|---|---|---|
| 0 | 0 | 10 | 90 | 100 |
| 50 | 5 | 10 | 85 | 100 |
| 100 | 10 | 10 | 80 | 100 |
| 150 | 15 | 10 | 75 | 100 |
| 200 | 20 | 10 | 70 | 100 |
| 250 | 25 | 10 | 65 | 100 |

**Table 2.2 Potassium Standard Formulation for use in Spectrometer**

| Potassium Standard ppm | Volume of .41% $KH_2PO_4$ in ml | Volume of 10% HCl ml | Volume of Deionized distilled $H_2O$ ml | Final volume of standard ml |
|---|---|---|---|---|
| 0 | 0 | 10 | 90 | 100 |
| 252.5 | 20 | 10 | 70 | 100 |
| 315.6 | 25 | 10 | 65 | 100 |
| 378.8 | 30 | 10 | 60 | 100 |
| 441.9 | 35 | 10 | 55 | 100 |
| 505 | 40 | 10 | 50 | 100 |
| 568.1 | 45 | 10 | 45 | 100 |

**Equation 2.2 Calculation for P estimation**

[P] in Plant Tissue Sample (% dry weight) = Instrument reading of P (mg/L) x P sample (0.015L/200mg) x 100

**Equation 2.3 Calculation for K estimation**

[K] in Plant Tissue Sample (% dry weight) = Instrument reading of K (mg/L) x K sample (0.015L/200g) x 100

### 2.2.6 Total Kjeldahl Nitrogen Measurements

A Spectrophotometer-Lachat QuikChem 8500 series 2 is used to analyze total nitrogen in the samples (QC 8500 Spectrophotometer, Lachat Instruments, Milwaukee, WI). To begin 0.2 g of plant tissue is measured into a 50 ml kjeldahl flask. 1.7g of a premixed potassium sulfate and cupric sulfate ($K_2SO4$ and $CuSO_4$) is added to each flask. The flasks are brought to the fume hood where 3.5 ml of concentrated sulfuric acid is added directly to each sample and then heated on a Kjeldahl microdigester for 40 minutes. After cooling for 10 minutes, 48 ml of deionized-distilled water is added to each flask to total 50 ml of solution. Flow injection analysis method for total nitrogen is used to analyze the samples (Wendt, 2000).

**Equation 2.4 Calculation for N estimation**

[N] in Plant Tissue Sample (% dry weight) = Instrument reading of N (mg/L) x autodilution factor x K sample (0.050 L/200g) x 100

### 2.2.7 Soil water content

To get an idea how the solar panels effect growing conditions. Soil water content is measured using a soil probe (a soil profile sampling tool) to collect the top 6 inches of soil in each of the AV and control experimental plots and areas within them (L, R, M); 3 samples in each plot and area are taken and then combined. The soil taken is weighed and then air dried by spreading soil thinly on paper in a greenhouse overnight and is weighed again to determine water content. The measurements were replicated on three separate random days September $19^{th}$, October $5^{th}$, and October $11^{th}$ 2018.

**Equation 2.5 Calculation for Soil Water Content**

Soil Water Content g water per g dry soil = (Soil Fresh Weight (g) -Soil Dry Weight (g))/ (Soil Dry Weight (g))

### 2.2.8 Leaf Temperature

Leaf temperature is taken on the pepper plants to get an idea of how shading by the panels affects the temperature of the leaves of the crops. Left, right, middle designations are not done for this test because shading in experimental plots changes with the movement of the earth in relation to the sun so temperatures are taken wherever the shade of the panel was in the AV plots. For each experimental plot, 3 different mature leaves from the top of randomly selected plants are selected and leaf temperature is measured, and their average is recorded. This measurement was replicated for three random days in sunny conditions and 3 random days in cloudy conditions. The temperatures are taken at 3 times each day during the day at 9 am, 12 pm, and 3 pm. Crop leaf temperature is measured with a Cen-Tech Infrared thermometer with a laser for accuracy (Harbor Freight Tools Calabasas, CA) at the center of the leaf.

### 2.2.9 Statistical Analysis

Analysis of variance is performed on all data with SAS statistical software (version 9.4, Cary, NC) (Damon and Harvey, 1987). There are two replicates for this experiment; the north and south positioned panel rows both contained experimental plots with gap distance between panels of (2-ft, 3-ft, 4-ft, 5-ft) or no panel. For each crop biomass yields independent variables are gap distance between panels (2-ft, 3-ft, 4-ft, 5-ft) or no panel, and area (left, right, middle). Dependent variables are number of fruits or leaves, and fresh, and dry weights of each crop. Independent variables for measuring N P and K concentrations for each crop are gap and area as well. Dependent variables are level of N P and K. Light measurement independent variables are gap and area and dependent variable is light % of control plot full sun. Soil water content measurement independent variables are gap and area and the dependent variables are water content. For soil water content the replicates are panel and day.  Leaf temperature independent variables are time and gap and the dependent variable is leaf temperature. For leaf temperatures replication of experiment is done by panel and day. For all these measurements gap distance between panels is the variable of particular interest in this experiment. For yields, nutrients, and soil moisture results for the area within plot variable no significance is expected but it is added to increase the degrees of freedom of the experiment. In addition to ANOVA orthogonal polynomial contrasts are used to determine trends in gap distance from 2-ft to 5-ft plots, to determine relationship in area left, right, and middle, and to determine the differences in the control full sun plot versus under the panels in the AV plots. Significance between treatment means are determined by the F-test (Harvey and Damon, 1987).

For the Swiss chard and kale, a plant covariate is used to account for the fact that the transplants sometimes have more than one plant per planting space.

### 2.3 Results

### 2.3.1 Light Measurements

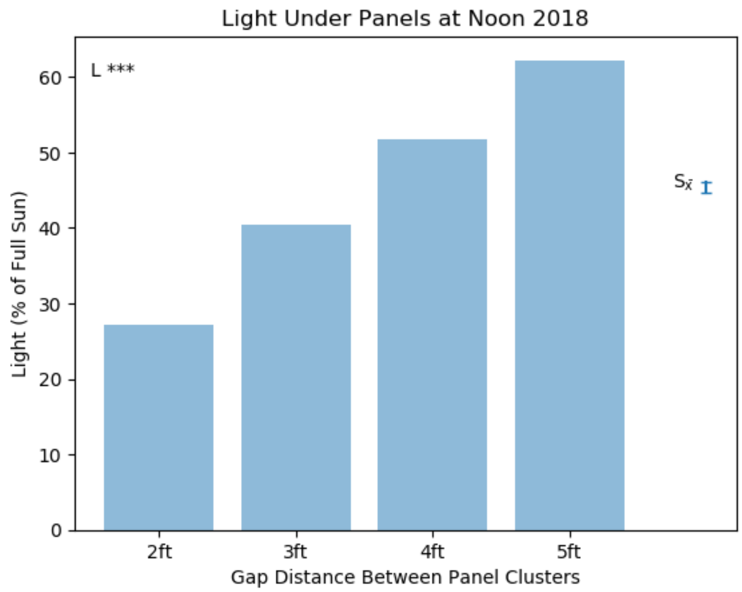


**Figure 2.2 Light Under Panels by Gap Distance Between Panels.**
The effect of gap distance between panels is significant on light percent of the full sun plots under panels at the crop level (P≤0.0001). For the AV plots with gap distances of 2-ft, 3-ft, 4-ft, or 5-ft, mean light under the panels at the crop level is 27%, 40%, 52%, and 62% of the full sun plots. For the AV plots, there is a linear (P<.0001) trend but no quadratic (P=0.3090) or cubic (P=0.8589) trend in light percent of the full sun plots at the crop level with increasing gap distance. Sample mean is 45% of the full sun light and $S_x$ = 1.32% of the full sun light. Significance between treatment (gap distance) means are determined by the F-test. L, Linear; $S_x$ , standard error of the sample mean;***, statistically significant (P≤ 0.001).

Light measurements were taken on June 21st, 2018, at noon when the sun was directly above the solar panels. Light measurements are taken to confirm the differing amounts of solar radiation below the panels in the AV experimental plots. However, in this study due to only one time being sampled there is only one area within plots (the middle area) that is in the shade. It is important to note that different areas within plots, left, right, and middle (L, R, M), will all receive different shading depending on the time of the day and position of the sun. We expect that all areas will receive similar amounts of shade because of the changing position of the sun throughout the day as it penetrates the gaps between the panels to reach all areas. The wider the gap distance the more light will penetrate from the L (west) and R (East) into area under the panels. The light measurements are made to establish how much radiation is reduced in the shade of the panels, and to show that there is a shading effect in the AV plots compared to the full sun control plots.

ANOVA shows there is a significant effect by the area within plots for light percent of full sun at the crop level under the panels ($P \leq 0.0001$); for the left area, the mean light is 60% of full sun plot light, for the right area, mean light is 60% of full sun plot light; and for the middle area, the mean light is 16% of the full sun plot light. Furthermore, for light percent of full sun under the panels at the crop level, orthogonal polynomial contrasts show there is a significant difference between the left and right areas versus the middle area ($P \leq 0.0001$) with a mean of 60% of full sun light for the left and right area and a mean of 16% of full sun light for the middle area. There is also a significant interaction for gap x area ($P \leq .0001$). Gap distance between panels is found to have a significant effect in the left ($P < .0001$) and right area ($P < .0001$). For the left area, the AV plots with 2-ft, 3-ft, 4-ft, or 5-ft gap distances have a mean of 34%, 53%, 69%, and 85% light percent of the full sun plot at the crop level. For the right area the AV plots with 2-ft, 3-ft, 4-ft, or 5-ft gap distances have a mean of 34%, 51%, 69%, and 85% light percent of the full sun plot at the crop level. The significant interaction demonstrates that AV plot gap distance is significant in its effect on light percent at the crop level but at the time of testing it is not for the middle area below the panels. For the middle area where gap distance between panels is found to have no significant effect ($P = .6437$) on light percent of the full sun plot at the crop level the AV plots with 2-ft, 3-ft, 4-ft, and 5-ft gap distances have a mean of 14%, 18%, 17%, and 17% light percent of the full sun plot at the crop level. Because the light measurements were taken only at one time (when the sun was directly perpendicular to the panels) the middle area was shaded; the shading patterns of the system will change throughout the day so that all areas will receive similar light radiation. The significant interaction is just showing that the middle area received shade at the noon testing time. Overall the panels do reduce light by shading areas below them. In this instance the area that is shaded by the panels is the middle area, but the area in the direct shade should change throughout the day based on sun position. So, in the AV system, the panels are reducing light radiation to crops below the panels.

For gap distance between panels, the variable of particular interest in this study, ANOVA shows that there is a significant effect on light percent of full sun at the crop level under the panels ($P \leq 0.0001$) (Figure 2.2). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, or 5-ft, the light measurements are 27%, 40%, 52%, or 62% of the full sun light, respectively (Figure 2.2). Orthogonal polynomial contrasts show the reduction in light for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) is linear in trend with light increasing with increasing gap distance between panels. There is no quadratic ($P=0.3090$) or cubic trend ($P=0.8589$) in light percent of full sun at the crop level with increasing gap distance between panels.

### 2.3.2 Swiss Chard Biomass Yields

#### 2.3.2.1 Swiss Chard Leaf Number Per Plant

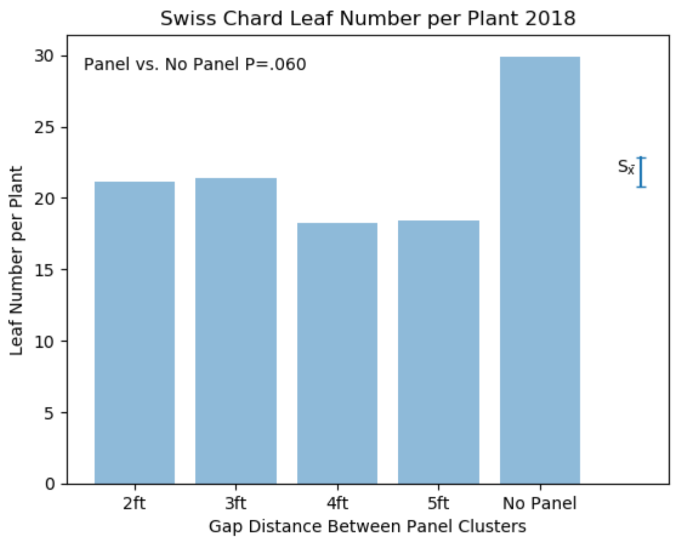


**Figure 2.3 Swiss Chard Leaf Number Per Plant Yields by Gap Distance Between Panels.**
The effect of gap distance between panels is not significant for Swiss chard number of leaves per plant (P=0.2265). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, the mean leaf number per plants is 21, 21, 18, 18 and 30. For the AV plots there is no linear (P=0.3195), quadratic (P=0.7308), or cubic (P=0.3536) trend in leaves per plant with increasing gap distance. Contrasts showed there is a significant difference in leaf number per plants (P=0.060 between the AV experimental plots with a mean of 20 leaves per plant and the control plots with a mean of 30 leaves per plant (Panel vs. No Panel). Sample mean is 22 leaves per plant and $S_x$ = 2.05 leaves per plant. Significance between treatments (gap distance) means are determined by the F-test. $S_x$ , standard error of the mean;*, statistically significant ($P \leq 0.05$).

ANOVA shows that there is no significant effect by area within plots for Swiss chard leaf number per plant (P=0.8315); for the left area mean leaf number per plant is 22, for the right area mean leaf number per plant is 23, and for the middle area mean leaf number per plant is 21. Furthermore, for Swiss chard leaf number per plant orthogonal polynomial contrasts show no significant difference between the left and right areas versus the middle area (P=0.7482). There is no interaction between gap and area (P=0.9988) variables for Swiss chard leaf per plant.

For gap distance between panels, the variable of particular interest in this study, ANOVA shows no significant effect (P=0.2265) on leaf number per plant yields (Figure 2.3). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, the mean Swiss chard leaf number per plants are 21, 21, 18.24, 18, and 30. Orthogonal polynomial contrasts show that Swiss chard leaf number per plant in the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) does not fit a linear (P=0.3195), quadratic (P=0.7308), or a cubic trend (P=0.3536) with increasing gap distance between panels. When contrasting the mean of the control plots (plants grown in the full sun) versus the mean of all of the AV plots (plants grown under the panels), there is a significant difference in leaf number per plant (P=0.060); the mean of the full sun control plots is 30 leaves per plant and the mean of the AV plots is 20 leaves per plant. Overall Swiss chard leaf number per plant yields for the AV plots with gap distance between panels of 2-ft, 3-ft, 4-ft, or 5-ft plots are 71%, 72%, 61%, and 61% of the control plot yield.

### 2.3.2.2 Swiss Chard Fresh Weight Per Plant

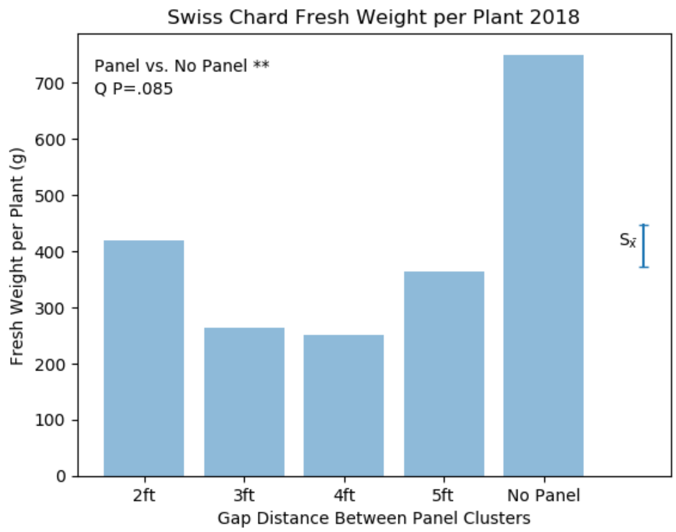


**Figure 2.4 Swiss Chard Fresh Weight Per Plant Yields by Gap Distance Between Panels.**
The effect of gap distance between panels is significant for Swiss chard fresh weight per plant (P=.0080). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel there is mean fresh weights of 418 g, 263 g, 252 g, 364 g, and 750 g, respectively, per plant. For the AV plots there is no linear (P=0.6240), quadratic (P=0.0847), or cubic (P=0.9765) trend in fresh weight per plant yields with increasing gap distance. Contrasts show there is a significant difference in fresh weight per plant (P=0.0011) between the AV plots with a mean fresh weight of 324 g versus the control plots with a mean fresh weight of 750 g (Panel vs. No Panel). Sample mean is 410 g per plant and $S_x = 73$ g per plant. Significance between treatment (gap distance) means is determined by the F-test. Q, quadratic; $S_x$, standard error of the sample mean;**, statistically significant ($P \leq 0.01$); ns, not statistically significant (P>0.05).

ANOVA shows that there is no significant effect by area within plots for Swiss chard fresh weight per plant (P=0.5923); for left area mean fresh weight per plant is 360 g; for the right area mean the fresh weight per plant is 428 g, and for the middle area mean fresh weight per plant the is 440 g. Furthermore, using orthogonal polynomial contrasts no significant difference is found between the left and right areas versus the middle area (P=0.4778) for Swiss chard fresh weight per plant. There is no interaction found between gap and area (P=0.2808) for Swiss chard fresh weight per plant.

For gap distance between panels, the variable of particular interest in this study, ANOVA shows that there is a significant effect (P=0.0080) on Swiss chard fresh weight per plant yields (Figure 2.4). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, the mean Swiss chard fresh weights per plant are 418 g, 263 g, 252 g, 364 g, and 750 g. Orthogonal polynomial contrasts show that the trend of Swiss chard fresh weight per plant in the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) does not fit a linear (P=0.6240), quadratic (P=0.0847), or cubic trend (P=0.9765) with increasing gap distance between panels . When contrasting the mean of the control plots (plants grown in the full sun) versus the mean of all of the AV plots (plants grown under the panels), there is a significant difference found in Swiss chard fresh weight per plant (P=0.0011); the mean of the full sun control plots Swiss chard fresh weights is 750 g and the mean of the AV plots swish chard fresh weights is 324 g. Overall, Swiss chard fresh weight per plants for the AV plots with gaps of 2-ft, 3-ft, 4-ft, or 5-ft plots are 56%, 35%, 34%, and 49% of the control yield.

### 2.3.2.3 Swiss Chard Dry Weight Per Plant

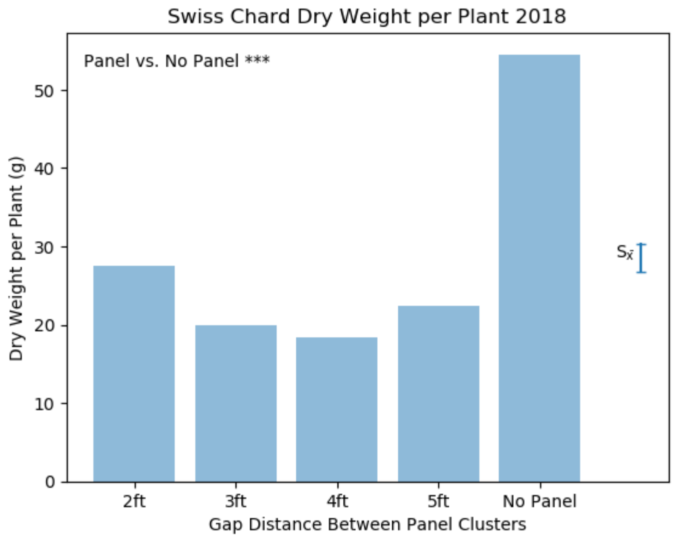


**Figure 2.5 Swiss Chard Dry Weight Per Plant Yields by Gap Distance Between Panels.**
The effect of gap distance between panels is significant for Swiss chard dry weight per plant (P=.0003). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel there are mean dry weights of 27 g, 20 g, 18 g, 22 g, and 55 g respectively. For the AV plots there is no linear (P=.3477), quadratic (P=.1328), or cubic (P=.9984) trend in dry weight per plant yields with increasing gap distance. Contrasts show there is a significant difference in dry weight per plant (P<.0001) when comparing all of the AV plots with mean dry weight of 55 g versus the control plots with mean dry weight of 22 g (Panel vs. No Panel). Sample mean is 29 g per plant and $S_x$ = 3.70 g per plant. Significance between treatment (gap distance) means is determined by the F-test. $S_x$ , standard error of the sample mean;***, statistically significant (P≤ 0.001); ns, not statistically significant (P>0.05).

ANOVA shows that there is no significant effect by area within plots for Swiss chard dry weight per plant (P=.4349); for the left area the mean dry weight per plant is 25 g, for the right area the mean dry weight per plant is 30.49 g, and for the middle area the mean dry weight per plant is 30 g. Specifically, using orthogonal polynomial contrasts no significant difference is found between the left and right areas versus the middle area (P=.5655) for Swiss chard dry weight per plant. There is no interaction found between gap and area (P=.2034) for Swiss chard dry weight per plant.

For gap distance between panels, the variable of particular interest in this study, ANOVA shows that there is a significant effect (P=.0003) on Swiss chard dry weight per plant yields (Figure 2.5). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel the mean Swiss chard dry weights per plant are 28 g, 20 g, 18 g, 22 g, and 55 g. Orthogonal polynomial contrasts show that the trend of Swiss chard dry weight per plant for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) does not fit a linear (P=.3477), quadratic (P=.1328), or cubic (P=.9984) trend with increasing gap distance between panels. When contrasting the mean of the control plots (plants grown in the full sun) versus the mean of all the AV plots (plants grown under the panels) there is a significant difference found in Swiss chard dry weight per plant (P<.0001); the mean of the full sun control plots is 55 g and the AV plot mean is only 22 g. Overall, Swiss chard dry weights per plant for the 2-ft, 3-ft, 4-ft, or 5-ft plots are 50%, 36%, 34%, and 41% of the control plot yield.

### 2.3.3 Swiss Chard Nutrient Levels

#### 2.3.3.1 Swiss Chard Nitrogen

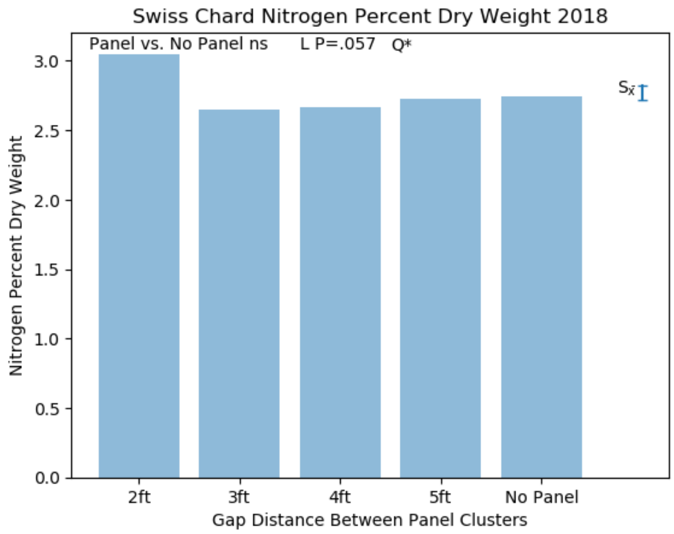


**Figure 2.6 Swiss Chard Nitrogen Levels by Gap Distance Between Panels.** The effect of gap distance between panels is significant for Swiss chard N percent by dry weight (P=0.0824). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel there are mean N percent by dry weights of 3.05%, 2.65%, 2.67%, 2.73%, and 2.74% respectively. For the AV plots there is a quadratic (P=0.0390) trend, almost a linear (P=0.0566) trend, and no cubic (P=0.4006) trend in Swiss chard N percent by dry weight with increasing gap distance. Contrasts show there is no significant difference in N percent by dry weight (P=.7485) when comparing all the AV plots with a mean of 2.77% N versus the control plots with mean of 2.74% N (Panel vs. no Panel). Sample mean is 2.77% N and $S_x$ = 0.10% N. Significance between treatment (gap distance) means is determined by the F-test. L, Linear; Q, quadratic; $S_x$ , standard error of the sample mean;*, statistically significant (P≤ 0.05); ns, not statistically significant (P>0.05).

ANOVA shows that there is no significant effect by area within plots for Swiss chard N percent by dry weight (P=0.4016); for the left area, the mean N percent by dry weight is 2.69%, for the right area, the mean N percent by dry weight is 2.84%, and for the middle area, the mean N percent by dry weight is 2.77%. Specifically, using orthogonal polynomial contrasts no significant difference is found between the left and right areas versus the middle area (P=0.9896) for Swiss chard N percent by dry weight.

There is no interaction between gap and area (P=.0789) for Swiss chard N percent by dry weight.

For gap distance between panels, the variable of particular interest in this study, ANOVA shows that there is a significant effect on Swiss chard N percent by dry weight (P=0.0824) (Figure 2.6). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel the mean N percent by dry weights are 3.05%, 2.65%, 2.67%, 2.73%, and 2.74%. Orthogonal polynomial contrasts show that the trend of N percent by dry weight for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) fits a quadratic (P=0.0390) trend, almost fits a linear (P=0.0566) trend, and does not fit a cubic (P=0.4006) trend with increasing gap distance between panels . When contrasting the mean of the control plots (plants grown in the full sun) versus the mean of all the AV plots (plants grown under the panels) there is no significant difference found in Swiss chard N percent by dry weight (P=0.7485); the mean N percent by dry weight of the full sun control plots was 2.74% and the mean N percent by dry weight of the AV plots is 2.77%.

### 2.3.3.2 Swiss Chard Phosphorus

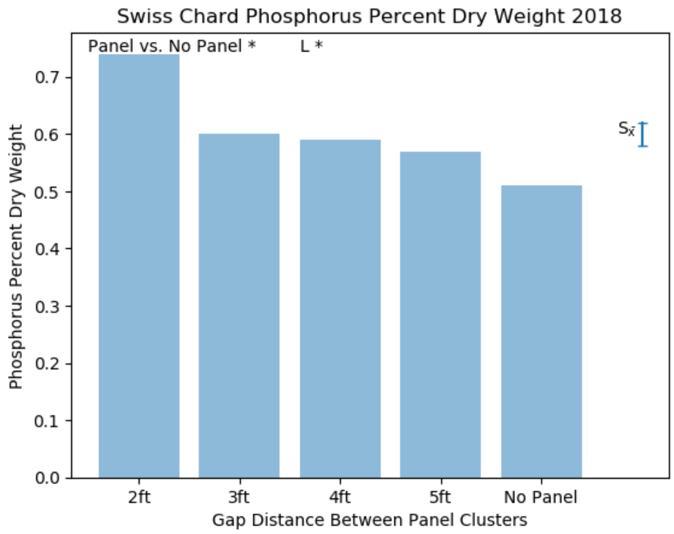


**Figure 2.7 Swiss Chard Phosphorus Levels by Gap Distance Between Panels.** The effect of gap distance between panels is significant for Swiss chard P percent by dry weight (P=0.0138). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel there are mean P percent by dry weights of 0.74%, 0.60%, 0.59%, 0.57%, and 0.51% respectively. For the AV plots there is a linear trend of declining pepper P percent by dry weight (P=0.0119), but no quadratic (P=0.1363) or no cubic (P=0.3810) trend with increasing gap distance. Contrasts show there is a significant difference in P percent by dry weight (P=.0206) when comparing all of the AV plots with mean of 0.63% P versus the control plots with mean of 0.51% P (Panel vs. No Panel). Sample mean is 0.60% P and $S_x$ = 0.04% P. Significance between treatment (gap distance) is determined by the F-test. L, Linear; $S_x$ , standard error of the sample mean;*, statistically significant ($P \leq 0.05$); ns, not statistically significant (P>0.05).

ANOVA shows that there is no significant effect by area within plots for Swiss chard P percent by dry weight (P=0.6827); for the left area, the mean P percent by dry weight is 0.58%, for the right area, the mean P percent by dry weight is 0.62%, and for the middle area, the mean P percent by dry weight is 0.61%. Furthermore, using orthogonal polynomial contrasts no significant difference is found between the left and right areas versus the middle area (P=0.9021) for Swiss chard P percent by dry weight. There is no interaction between gap and area for Swiss chard P percent by dry weight (P=0.7201).

For gap distance between panels, the variable of particular interest in this study, ANOVA shows that there is a significant effect on Swiss chard P percent by dry weight (P=0.0138) (Figure 2.7). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, the mean P percent by dry weights are 0.74%, 0.60%, 0.59%, 0.57%, and 0.51%. Orthogonal polynomial contrasts show that the trend of P percent by dry weight for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) fits a linear decline (P=0.0119) but does not fit a quadratic (P=0.1363) or cubic (P=0.3810) trend with increasing gap distance between panels . When contrasting the mean of the control plots (plants grown in the full sun) versus the mean of all of the AV plots (plants grown under the panels) there is a significant difference found in Swiss chard P percent by dry weight (P=.0206); the mean P percent by dry weight of the  full sun control plots is 0.51% and the mean P percent by dry weight of the AV plots is 0.63%.

### 2.3.3.3 Swiss Chard Potassium

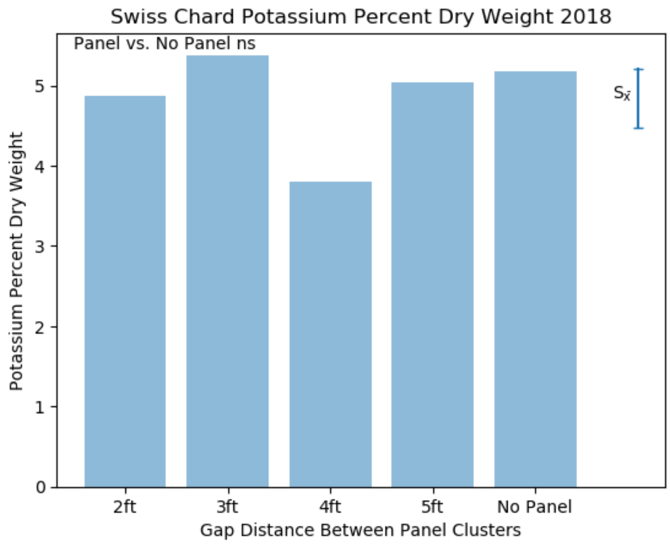


**Figure 2.8 Swiss Chard Potassium Levels by Gap Distance Between Panels.** The effect of gap distance between panels is not significant for Swiss chard K percent by dry weight (P=0.5735). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel there are mean K percent by dry weights of 4.87%, 5.38%, 3.80%, 5.04%, and 5.18% respectively. For the AV plots there is no linear (P=.7477), quadratic (P=.6150), or cubic (P=.1464) trend in Swiss chard K percent by dry weight with increasing gap distance. Contrasts show there is no significant difference in K percent by dry weight (P=0.6231) when comparing all of the AV plots with mean of 4.77% K versus the control plots with mean of 5.18% K (Panel vs. No Panel). Sample mean is 4.84% K and $S_x$ = 0.72% K. Significance between treatment (gap distance) is determined by the F-test. $S_x$, standard error of the sample mean; ns, not statistically significant (P>0.05).

ANOVA shows no significant effect by area within plots for Swiss chard K percent by dry weight (P=0.7669); for the left area, the mean K percent by dry weight is 4.83%; for the right area, the mean K percent by dry weight is 4.49% K, and for the middle area, the mean K percent by dry weight is 5.18%. Furthermore, using orthogonal polynomial contrasts, no significant difference is found between the left and right areas versus the middle area (P=0.5021) for Swiss chard K percent by dry weight. There is no interaction found between gap and area for Swiss chard K percent by dry weight (P=0.9982).

For gap distance between panels, the variable of particular interest in this study, ANOVA shows that there is a significant effect on Swiss chard K percent by dry weight ($P=0.5735$) (Figure 2.8). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, the mean K percent by dry weights are 4.87%, 5.38%, 3.80%, 5.04%, or 5.18%. Orthogonal polynomial contrasts show that the trend of K percent by dry weight for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) does not fit a linear ($P=0.7477$), quadratic ($P=0.6150$), or cubic ($P=0.1464$) trend with increasing gap distance between panels. When contrasting the mean of the control plots (plants grown in the full sun) versus the mean of all of the AV plots (plants grown under the panels), there is no significant difference found in Swiss chard K percent by dry weight ($P=.6231$); the mean K percent by dry weight of the full sun control plots is 5.18% and the mean K percent by dry weight of the AV plots is 4.77%.

### 2.3.4 Kale Biomass Yields

#### 2.3.4.1 Kale Leaf Number Per Plant

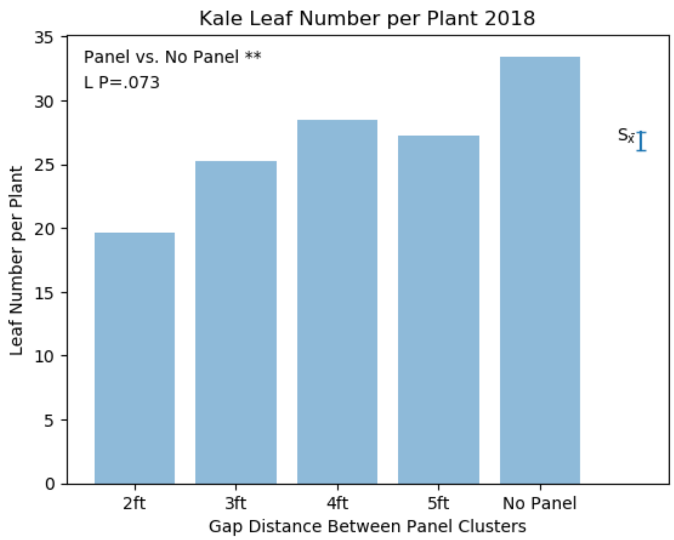


**Figure 2.9 Kale Leaf Number Per Plant Yields by Gap Distance Between Panels.** The effect of gap distance between panels is significant for kale leaf number per plant (P=0.0397). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel there are mean leaf numbers per plant of 20, 25, 28, 27, or 33 respectively. For the AV plots, there is a linear (P=.0734) trend and not a quadratic (P=.2661) or cubic (P=.7516) trend in leaf per plant yields with increasing gap distance. Contrasts show there is a significant difference in leaves per plant (P=.0048) when comparing all of the AV plots with a mean of 25 leaves per plant versus the control plots with a mean of 33 leaves per plant (Panel vs. No Panel). Sample mean is 28 leaves per plant and $S_x = 2$ leaves per plant. Significance between treatment (gap distance) means is determined by the F-test. L, Linear; $S_x$ , standard error of the sample mean;*, statistically significant ($P\leq 0.05$); **, highly statistically significant ($P\leq 0.01$); ns, not statistically significant ($P>0.05$).

ANOVA shows that there is no significant effect by area within plots for kale leaf number per plant (P=0.7841); for the left area, the mean leaf number per plant is 27; for the right area, the mean leaf number per plant is 26, and for the middle area, the mean leaf number per plant is 28. Specifically, using orthogonal polynomial contrasts, no significant difference is found between the left and right areas versus the middle area

(P=0.5043) for kale leaf number per plant. There is no interaction between gap and area (P=0.6436) for kale leaf number per plant.

For gap distance between panels, the variable of particular interest in this study, ANOVA shows that there is a significant effect on kale leaf number per plant yields (P=0.0397) (Figure 2.9). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, the mean kale leaf numbers per plant are 20, 25, 28., 27, or 33. Orthogonal polynomial contrasts show that the trend of kale leaf number per plant for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) does fit a linear P=0.0734) trend and not a quadratic (P=0.2661) or cubic (P=0.7516) trend with increasing gap distance between panels. When contrasting the mean of the control plots (plants grown in the full sun) versus the mean of all of the AV plots (plants grown under the panels) , there is a significant difference found in kale leaf numbers per plant (P=.0048); the mean leaf number of the control plots is 33 leaves per plant and the mean leaf number of the AV plots is 25 leaves per plant. Overall, kale leaf numbers per plant for the 2-ft, 3-ft, 4-ft, or 5-ft plots are 59%, 76%, 85%, and 81% of the full sun control plot.

### 2.3.4.2 Kale Fresh Weight Per Plant

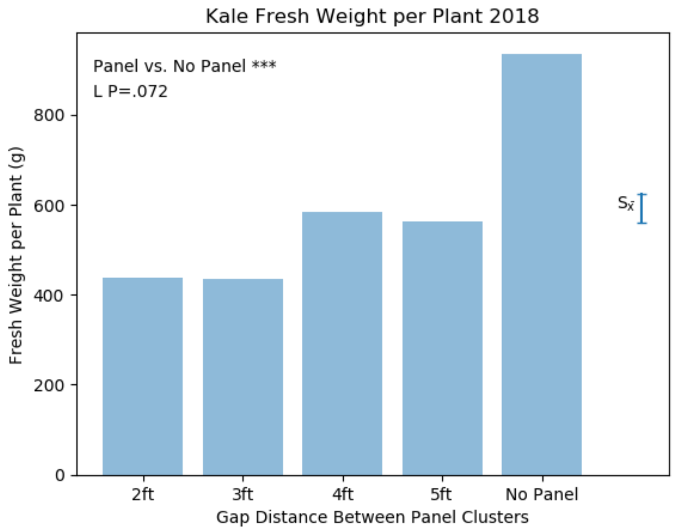


**Figure 2.10 Kale Fresh Weight Per Plant Yields by Gap Distance Between Panels.** The effect of gap distance between panels is significant for kale fresh weight per plant (P=0.0008). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel there are mean fresh weights per plant of 437 g, 436 g, 583 g, 562 g, and 935 g, respectively. For the AV plots, there is a linear (P=0.0721) trend and not a quadratic (P=0.6506) or cubic (P=0.3127) trend in fresh weight per plant yields with increasing gap distance. Contrasts show there is a significant difference in fresh weight per plant (P≤0.0001) when comparing all of the AV plots with a mean fresh weight per plant of 505 g versus the control plots with a mean fresh weight per plant of 935 g (Panel vs. No Panel). Sample mean is 591 g per plant and $S_x$= 64 g per plant. Significance between treatment (gap distance) means is determined by the F-test. L, Linear; $S_x$ , standard error of the sample mean; *, statistically significant (P≤ 0.05); ***, statistically significant (P≤0.001); ns, not statistically significant (P>0.05).

ANOVA shows that there is no significant effect found by area within plots for kale fresh weight per plant (P=0.5629); for the left area, the mean fresh weight per plant is 572 g; for the right area, the mean fresh weight per plant is 638 g, and for the middle area, the mean fresh weight per plant is 561 g. Specifically, using orthogonal polynomial contrasts, no significant difference is found between the left and right areas versus the middle area (P=0.4929) for kale fresh weight per plant. There is no interaction between gap and area (P=0.5380) for kale fresh weight per plant.

For gap distance between panels, the variable of particular interest in this study, ANOVA shows that there is a significant effect on kale fresh weight per plant yields (P=0.0008) (Figure 2.10). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, the mean kale fresh weights per plant are 437 g, 436 g, 583 g, 562 g, and 935 g. Orthogonal polynomial contrasts show that the trend of kale fresh weight per plant for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) does fit a linear (P=0.0721) trend and not a quadratic (P=0.6506) or cubic (P=0.3127) trend with increasing gap distance between panels. When contrasting the mean of the control plots (plants grown in full sun) versus the mean of all of the AV plots (plants grown under the panels), there is a significant difference found in kale fresh weight per plant (P<0.0001); the mean fresh weight per plant of the control plots is 935 g and the mean fresh weight per plant of the AV plots is 505 g . Overall, kale fresh weights per plant for the 2-ft, 3-ft, 4-ft, or 5-ft plots are 47%, 47%, 62%, and 60% of the control yield.

#### 2.3.4.3 Kale Dry Weight Per Plant

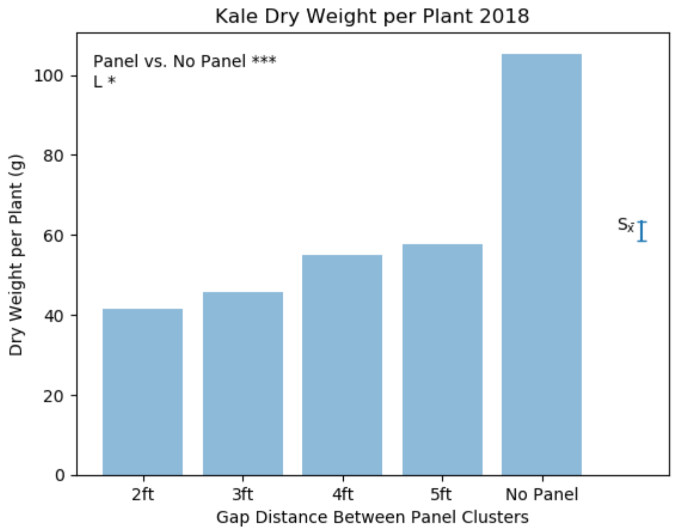


**Figure 2.11 Kale Dry Weight Per Plant Yields by Gap Distance Between Panels.** The effect of gap distance between panels is significant for kale dry weight per plant (P≤0.0001). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel there are mean dry weights per plant of 41 g, 46 g, 55 g, 58 g, or 105 g respectively. For the AV plots, there is a linear (P=0.0160) trend and not a quadratic (P=.6251) or cubic (P=.6246) trend in dry weight per plant yields with increasing gap distance. Contrasts show there is a significant difference in dry weight per plant (P<.0001) when comparing all of the AV plots with a mean dry weight per plant of 105 g versus the control plots with a mean fresh weight per plant of 50 g (Panel vs. No Panel). Sample mean is 61 g per plant and $S_x$= 5 g per plant. Significance between treatment (gap distance) means is determined by the F-test. L, Linear; $S_x$ , standard error of the mean;*, statistically significant (P≤ 0.05); ***, highly statistically significant (P≤ 0.001); ns, not statistically significant (P>0.05).

ANOVA shows that there is no significant effect found by area within plots for kale dry weight per plant (P=0.3748); for the left area, the mean dry weight per plant is 60 g; for the right area, the mean dry weight per plant is 66g; and for the middle area, the mean dry weight per plant is 58 g. Specifically, using orthogonal polynomial contrasts, no significant difference is found between the left and right areas versus the middle area (P=0.3007) for kale dry weight per plant. There is no interaction between gap and area (P=.3372) for kale dry weight per plant.

For gap distance between panels, the variable of particular interest in this study, ANOVA shows that there is a significant effect on kale dry weight per plant yields ($P<0.0001$) (Figure 2.11). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, the mean kale dry weights per plant are 41 g, 46 g, 55 g, 58 g, or 105 g. Orthogonal polynomial contrasts show that the trend of kale dry weight per plant for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) is linear ($P=0.0160$) and not quadratic ($P=0.6251$) or cubic ($P=0.6246$) with increasing gap distance between panels. When contrasting the control plots (plants grown in the full sun) versus the mean of all of the AV plots (plants grown under the panels), there is a significant difference found in kale dry weight per plant ($P<.0001$); the mean dry weight per plant of the control plots is 105 g and the mean dry weight per plant of the AV plots is 50 g. Kale dry weights per plant for the 2-ft, 3-ft, 4-ft, or 5-ft plots are 39%, 43%, 52%, and 55% of the control yield.

### 2.3.5 Kale Nutrient Levels

#### 2.3.5.1 Kale Nitrogen

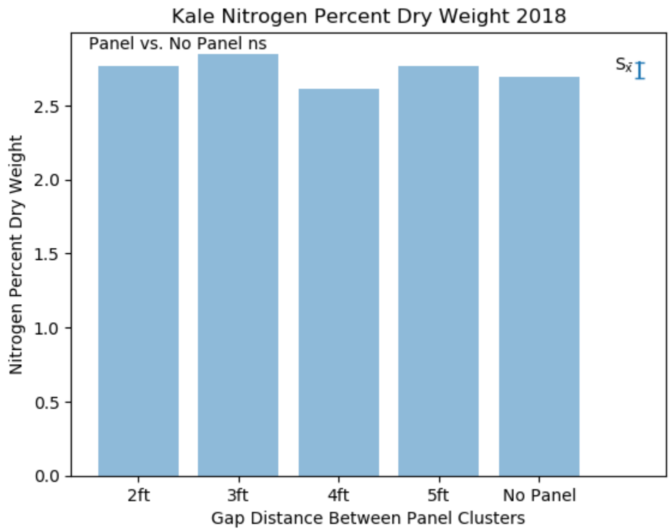


**Figure 2.12 Kale Nitrogen Levels by Gap Distance Between Panels.**
The effect of gap distance between panels is not significant for Kale N percent by dry weight (P=0.6259). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel there are mean N percent by dry weights of 2.77%, 2.85%, 2.61%, 2.77%, or 2.69%, respectively. For the AV plots there is no linear (P=0.9072), quadratic (P=9463), or cubic (P=.1396) trend in pepper N percent by dry weight with increasing gap distance. Contrasts show there is no significant difference in N percent by dry weight (P=0.7218) when comparing all of the AV plots with a mean f 2.69% N versus the control plot with a mean of 2.75% N (Panel vs. No Panel). Sample mean is 2.74% N and $S_x$ = 0.11% N. Significance between treatment (gaps distance) means is determined by the F-test. $S_x$ , standard error of the sample mean; ns, not statistically significant (P>0.05).

ANOVA shows that there is no significant effect by area within plots for kale N percent by dry weight (P=.9094); for the left area, the mean N percent by dry weight is 2.76% for the right area, the mean N percent by dry weight is 2.74%, and for the middle area, the mean N percent by dry weight is 2.71%. , Furthermore, using orthogonal polynomial contrasts no significant difference is found between the left and right areas versus the middle area (P=0.8490) for kale N percent by dry weight. There is no interaction between gap and area (P=0.7706) for kale N percent by dry weight.

For gap distance between panels, the variable of particular interest in this study, ANOVA shows that there is no significant effect on kale N percent by dry weight (P=0.6259) (Figure 2.12). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel the mean N percent by dry weights are 2.77%, 2.85%, 2.61%, 2.77%, or 2.69%. Orthogonal polynomial contrasts show that the trend of N percent by dry weight for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) does not a linear (P=0.9072), quadratic (P=.9469), or cubic (P=.1396) trend with increasing gap distance between panels. When contrasting the mean of the control plots (plants grown in the full sun) versus the mean of all of the AV plots (plants grown under the panels) there is no significant difference found in kale N percent by dry weight (P=0.7218); the mean N percent by dry weight of the full sun control plots is 2.69% and the mean N percent by dry weight of the AV plots is 2.75%.

### 2.3.5.2 Kale Phosphorus

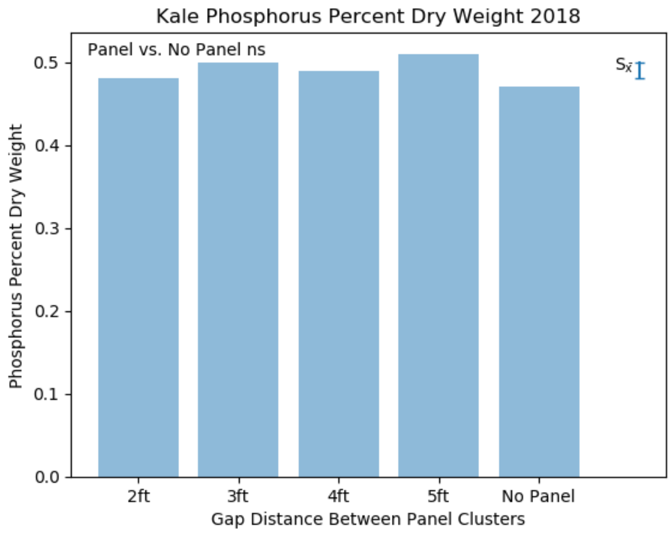


**Figure 2.13 Kale Phosphorus Levels by Gap Distance Between Panels.**
The effect of gap distance between panels is not significant for kale P percent by dry weight (P=0.4622). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel there are mean P percent by dry weights of 0.48%, 0.50%, 0.49%, 0.51%, and 0.47% respectively. For the AV plots there is no linear (P=0.3883), quadratic (P=0.9149), or cubic (P=.4801) trend in pepper P percent by dry weight with increasing gap distance. Contrasts show there is no significant difference in P percent by dry weight (P=0.1371) when comparing all of the AV plots with a mean of 49% P versus the control plots with a mean of .47% P (Panel vs. No Panel). Sample mean is 0.49% P and $S_{x}$ = 0.02% P. Significance between treatment (gap distance) means is determined by the F-test. $S_{x}$, standard error of the mean; ns, not statistically significant (P>0.05).

ANOVA shows that there is no significant effect by area within plots for P percent by dry weight (P=0.4430); for the left area, the mean P percent by dry weight is 0.50%; for the right area, the mean P percent by dry weight is 0.48%, and for the middle area, the mean P percent by dry weight is 0.49%. Furthermore, using orthogonal polynomial contrasts no significant difference is found between the left and right areas versus the middle area (P=0.8237) for kale P percent by dry weight. There is no interaction between gap and area (P=0.8908) for kale P percent by dry weight.

For gap distance between panels, the variable of particular interest in this study, ANOVA shows that there is no significant effect on kale P percent by dry weight

(P=0.4622) (Figure 2.13). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel the mean P percent by dry weights are 0.48%, 0.50%, 0.49%, 0.51%, or 0.47%. Orthogonal polynomial contrasts show that the trend of P percent by dry weight for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) does not fit a linear (P=0.3883), a quadratic (P=0.9149), or cubic (P=0.4801) trend with increasing gap distance between panels. When contrasting the mean of the control plots (plants grown in the full sun) versus the mean of all of the AV plots (plants grown under the panels) there is no significant difference found in kale P percent by dry weight (P=0.1371); the mean P percent by dry weight of the full sun control plots is 0.47% and the mean P percent by dry weight of the AV plots is 0.49%.

#### 2.3.5.3 Kale Potassium

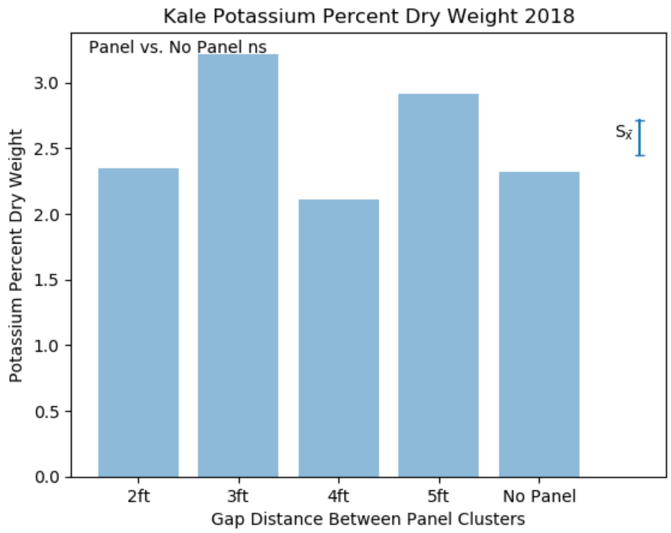


**Figure 2.14 Kale Potassium Levels by Gap Distance Between Panels.**
The effect of gap distance between panels is significant for kale K percent by dry weight (P=0.0570). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel there are mean K percent by dry weights of 2.35%, 3.22%, 2.11%, 2.92%, 2.32%, respectively. For the AV plots there is no linear (P=0.6251) or quadratic (P=0.9130) trend; there is a cubic (P=.0060) trend in pepper K percent by dry weight with increasing gap distance. Contrasts show there is no significant difference in K percent dry weight (P=.2977) when comparing all of the AV plots with a mean of 2.65% K versus the control plots with a mean of 2.32% K (Panel vs. No Panel). Sample mean is 2.58% K and $S_x$ = 0.27% K. Significance between treatment (gap distance) means is determined by the F-test. $S_x$, standard error of the sample mean; **, statistically significant ($P \leq 0.01$); ns, not statistically significant ($P>0.05$).

ANOVA shows that there is no significant effect by area within plots for kale K percent by dry weight (P=0.7489); for the left area, the mean K percent by dry weight is 2.71%; for the right area, the mean K percent dry weight is 2.50%; and for the middle area, the mean K percent by dry weight is 2.54%. Furthermore, using orthogonal polynomial contrasts no significant difference is found between the left and right areas versus the middle area (P=0.8017) for kale K percent by dry weight. There is no interaction between gap and area (P=0.8526) for kale K percent by dry weight.

For gap distance between panels, the variable of particular interest in this study, ANOVA shows that there is a significant effect on kale K percent by dry weight ($P=0.0570$) (Figure 2.14). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel the mean K percent by dry weights are 2.35%, 3.22%, 2.11%, 2.92%, or 2.32%. Orthogonal polynomial contrasts show that the trend of kale K percent by dry weight for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) does not fit a linear ($P=.6251$) or quadratic ($P=0.9130$) trend, but did fit a cubic ($P=0.0060$) trend with increasing gap distance between panels. When contrasting the mean of the control plots (plants grown in the full sun) versus the mean of all of the AV plots (plants grown under the panels) there is no significant difference found in kale K percent by dry weight ($P=0.2977$); the mean K percent by dry weight of the full sun control plots is 2.32% and the mean K percent by dry weight of the AV plots is 2.65%.  Even though a cubic trend was significant it is not an accurate depiction of the results.

### 2.3.6 Pepper Biomass Yields

#### 2.3.6.1 Pepper Fruit Number Per Plant

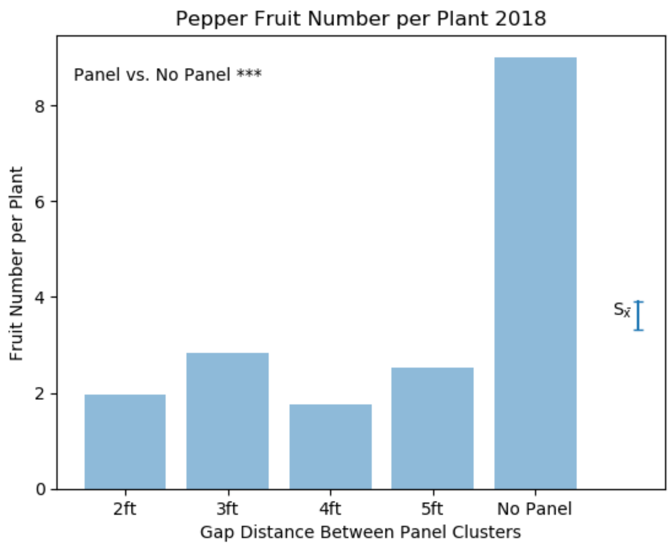


**Figure 2.15 Pepper Fruit Number Per Plant Yields by Gap Distance Between Panels.**
The effect of gap distance between panels is significant for pepper fruit number per plant (P≤0.0001). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, there are mean fruit numbers per plant of 1.96, 2.84, 1.75, 2.53, or 9.00 respectively. For the AV plots, there is no significant linear (P=.8168), quadratic (P=.9305), or cubic (P=.1708) trend in fruit number per plant yields with increasing gap distance. Contrasts show there is a significant difference in fruit number per plant (P≤.0001) when comparing all of the AV plots with a mean fruit number of 2.27 versus the control plots with a mean fruit number of 9.00 (Panel vs. No Panel). Sample mean is 3.61 fruits per plant and $S_x$ = 0.60 fruits per plant. Significance between treatment (gap distance) is determined by the F-test. $S_x$, standard error of the sample mean; ***, highly statistically significant (P≤ 0.001); ns, not statistically significant (P>0.05).

ANOVA shows that there is no significant effect by area within plots for pepper fruit number per plant (P=0.3848); for the left area, the mean fruit number per plant is 3.25; for the right area, the mean fruit number per plant is 4.14; and for the middle area, the mean fruit number per plant is 3.46. Specifically, using orthogonal polynomial contrasts, no significant difference is found between the left and right areas versus the middle area ($P=0.6843$) for pepper fruit number per plant. There is no interaction between gap and area ($P=0.8859$) for pepper fruit number per plant.

For gap distance between panels, the variable of particular interest in this study, ANOVA shows that there is a significant effect on pepper fruit number per plant yields ($P \leq 0.0001$) (Figure 2.15). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel the, mean pepper fruit numbers per plant are 1.96, 2.84, 1.75, 2.53, or 9.00. Orthogonal polynomial contrasts show that the trend of pepper fruit number per plant for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) does not fit a linear ($P=0.8168$), quadratic ($P=0.9305$), or cubic ($P=0.1708$) trend with increasing gap distance between panels. When contrasting the mean of the control plots (plants grown in the full sun) versus the mean of all of the AV plots (plants grown under panels), there is a significant difference found in pepper fruit number per plant ($P<.0001$); the mean fruit number per plant of the control plots is 9 and the mean fruit number per plant of the AV plots is 2.27. Overall, pepper fruit number per plant for the 2-ft, 3-ft, 4-ft, or 5-ft plots are 22%, 32%, 19%, and 28% of the control yield.

### 2.3.6.2 Pepper Fresh Weight Per Plant

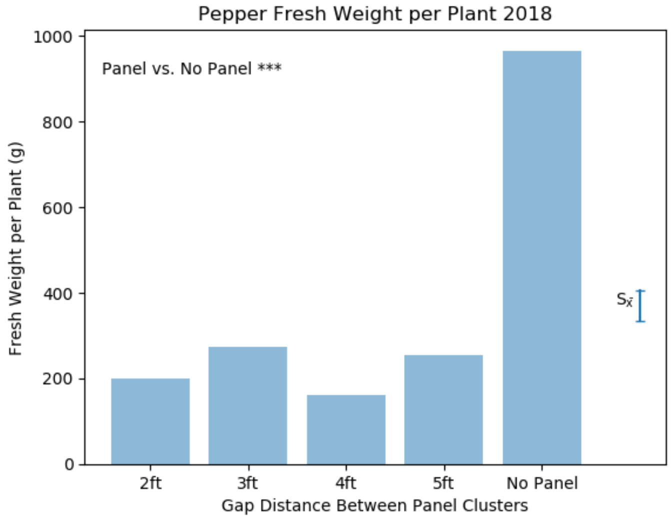


**Figure 2.16 Pepper Fresh Weight Per Plant Yields by Gap Distance Between Panels.** The effect of gap distance between panels is significant on pepper fresh weight per plant (P≤0.0001). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, there are mean fresh weights of 199 g, 273 g, 160, 253 g, and 965 g respectively. For the AV plots, there is no linear (P=0.8768), quadratic (P=0.8946), or cubic (P=0.2334) trend in fresh weight per plant yields with increasing gap distance. Contrasts show there is a significant difference in fresh weight per plant (P≤.0001) when comparing all of the AV plots with a mean fresh weight of 221 g versus the control plots with a mean fresh weight of 965 g (Panel vs. No Panel). Sample mean is 370 g per plant and $S_x$ = 71 g per plant. Significance between treatment (gap distance) means is determined by the F-test. $S_x$, standard error of the sample mean; ***, statistically significant (P≤ 0.001); ns, not statistically significant (P>0.05).

ANOVA shows that there is no significant effect by area within plots for pepper fresh weight per plant (P=0.5173); for the left area, the mean fresh weight per plant is 332 g; for the right area, the mean fresh weight per plant is 421 g; and for the middle area, the mean fresh weight per plant is 357 g. Specifically, using orthogonal polynomial contrasts, no significant difference is found between the left and right areas versus the middle area (P=0.7722) for pepper fresh weight per plant. There is no interaction between gap and area (P=0.8666) for pepper fresh weight per plant.

For gap distance between panels, the variable of particular interest in this study, ANOVA shows that there is a significant effect on pepper fresh weight per plant yields ($P<.0001$) (Figure 2.16). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, the mean pepper fresh weights per plant are 199 g, 273 g, 160 g, 253 g, and 965 g. Orthogonal polynomial contrasts show that the trend of pepper fresh weight per plant for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps ) does not fit a linear ($P=.8768$), quadratic ($P=.8946$), or cubic ($P=.2334$) trend with increasing gap distance between panels. When contrasting the mean of the control plots (plants grown in the full sun) versus the mean of all of the AV plots (plants grown under panels), there is a significant difference found in pepper fresh weight per plant ($P<.0001$); the mean fresh weight per plant for the control plots is 965 g and the mean fresh weight per plant for the AV plots is 221 g. Overall, pepper fresh weights per plant for the 2-ft, 3-ft, 4-ft, or 5-ft plots are 21%, 28%, 17%, and 26% of the control yield.

### 2.3.6.3 Pepper Dry Weight Per Plant

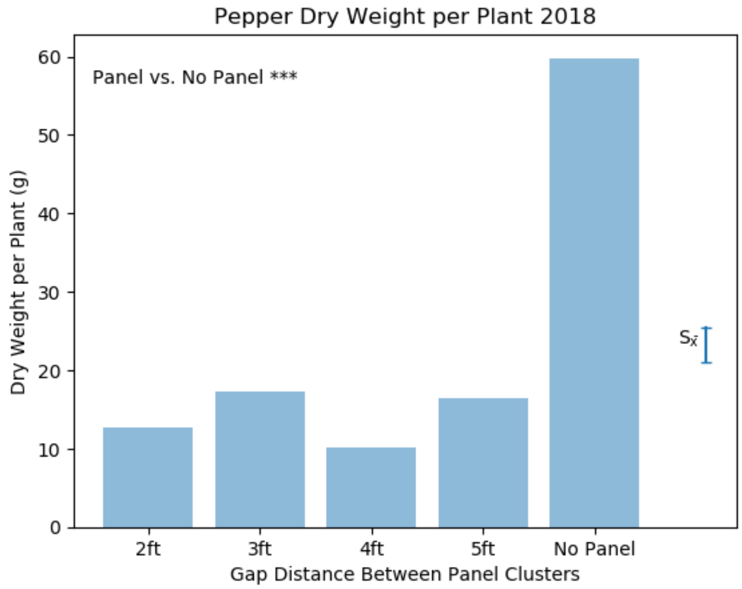


**Figure 2.17 Pepper Dry Weight Per Plant Yields by Gap Distance Between Panels.** The effect of gap distance between panels is significant on pepper dry weight per plant (P<.0001). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, there are mean dry weights of 13 g, 17 g, 10 g, 16 g, and 60 g respectively. For the AV plots, there is no linear (P=.8434), quadratic (P=.8457), or cubic (P=.2270) trend in dry weight per plant yields with increasing gap distance. Contrasts show there is a significant difference in dry weight per plant (P<.0001) when comparing all of the AV plots with a mean dry weight of 14 g versus the control plots with a mean dry weight of 60 g (Panel vs. No Panel). Sample mean is 23 g per plant and $S_x$ = 4 g per plant. Significance between treatment (gap distance) means is determined by the F-test. $S_x$, standard error of the sample mean; ***, statistically significant (P≤ 0.001); ns, not statistically significant (P>0.05).

ANOVA shows that there is no significant effect by area within plots for pepper dry weight per plant (P=.4677); for the left area, the mean dry weight per plant is 20.87g; for the right area, the mean dry weight per plant is 27 g; and for the middle area, the mean dry weight per plant is 22 g. Specifically, using orthogonal polynomial contrasts, no significant difference is found between the left and right areas versus the middle area (P=.7146) for pepper dry weight per plant. There is no interaction between gap and area (P=.7916) for pepper dry weight per plant.

For gap distance between panels, the variable of particular interest in this study, ANOVA shows that there is a significant effect on pepper dry weight per plant yields ($P<.0001$) (Figure 2.17). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, and no panel, the mean pepper dry weights per plant are 13 g, 17 g, 10 g, 16 g, and 60 g. Orthogonal polynomial contrasts show that the trend of pepper dry weight per plant for AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) does not fit a linear ($P=.8434$), quadratic ($P=.8457$), or cubic ($P=.2270$) trend with increasing gap distance between panels. When contrasting the mean of the control plots (plants grown in the full sun) versus the mean of all of the AV plots (plants grown under the panels), there is a significant difference found in pepper dry weight per plant ($P<.0001$); the mean dry weight per plant for the control plots is 60 g and the mean dry weight per plant for the AV plots is 14 g. Overall, pepper dry weights per plant for the 2-ft, 3-ft, 4-ft, or 5-ft plots are 21%, 29%, 17%, and 27% of the control yield.

### 2.3.7 Pepper Nutrient Levels

#### 2.3.7.1 Pepper Nitrogen

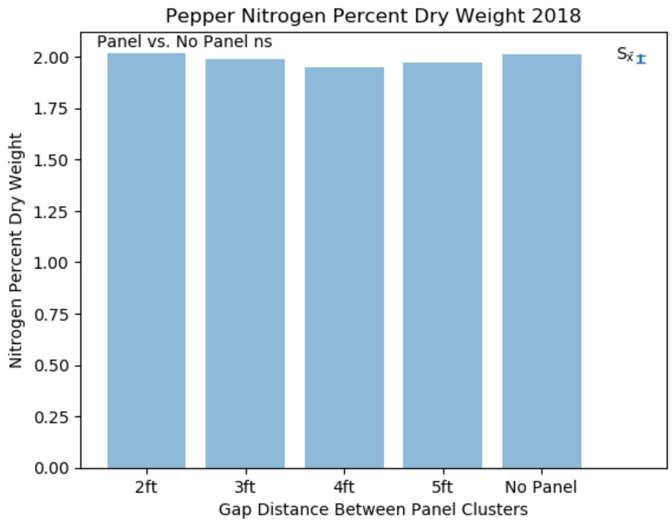


**Figure 2.18 Pepper Nitrogen Levels by Gap Distance Between Panels**
The effect of gap distance between panels is not significant on pepper N percent by dry weight (P=0.6073). For the experimental plots with gap distances of 2-ft, 3 -ft, 4-ft, 5-ft, or no panel there are mean N percent by dry weights of 2.02%, 1.99%, 1.95%, 1.97%, and 2.01% respectively. For the AV plots, there is no linear (P=0.2234), quadratic (P=.4589), or cubic (P=.6648) trend in pepper N percent by dry weight with increasing gap distance. Contrasts show there is no significant difference in pepper N percent by dry weight (P=0.5455) when comparing all of the AV plots with a mean of 1.98% N versus the control plots with a mean of 2.01% N (Panel vs. No Panel). Sample mean is 1.99% N and $S_x$ = 0.03% N. Significance between treatment (gap distance) means is determined by the F-test. $S_x$ , standard error of the sample mean; ns, not statistically significant (P>0.05).

ANOVA shows that there is no significant effect by area within plots for pepper N percent by dry weight (P=0.7800); for the left area, the mean N percent by dry weight is 1.98%; for the right area, the mean N percent by dry weight is 1.98%; and for the middle area, the mean N percent by dry weight is 2.00%. Furthermore, using orthogonal polynomial contrasts, no significant difference is found between the left and right areas versus the middle area (P=0.5013) for pepper N percent by dry weight. There is no interaction between gap and area (P=0.3953) for pepper N percent by dry weight.

For gap distance between panels, the variable of particular interest in this study, ANOVA shows that there is no significant effect on pepper N percent by dry weight ($P=0.6073$) (Figure 2.18). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, the mean N percent dry weights are 2.02%, 1.99%, 1.95%, 1.97%, and 2.01%. Orthogonal polynomial contrasts show that the trend of pepper N percent by dry weight for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) does not fit a linear ($P=0.92234$), quadratic ($P=0.4589$), or cubic ($P=0.6648$) trend with increasing gap distance between panels. When contrasting the mean of the control plots (plants grown in the full sun) versus the mean of all of the AV plots (plants grown under the panels) there is no significant difference in pepper N percent by dry weight ($P=0.5455$); the mean N percent by dry weight of the full sun control plots is 2.01% and the mean N percent by dry weight of the AV plots is 1.98%.

### 2.3.7.2 Pepper Phosphorus

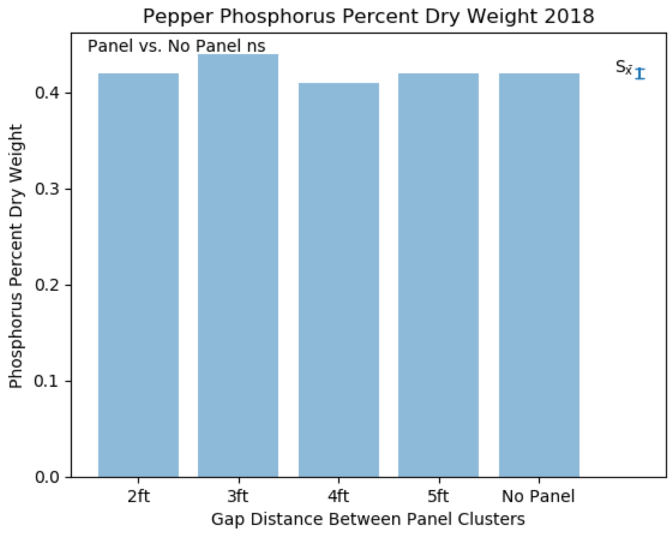


**Figure 2.19 Pepper Phosphorus Levels by Gap Distance Between Panels.**
The effect of gap distance between panels is not significant on pepper P percent by dry weight (P=0.1304). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, there are mean P percent by dry weights of 0.42%, 0.44%, 0.41%, 0.42%, and 0.42% respectively. For the AV plots, there is no linear (P=0.4727) or quadratic (P=0.2672) trend; there is a cubic (P=0.0315) trend in pepper P percent by dry weight with increasing gap distance. Contrasts show there is no significant difference in pepper P percent by dry weight (P=0.3462) when comparing all of the AV plots with a mean of 0.43% P versus the control plots with a mean of 0.42% P (Panel vs. No Panel). Sample mean is 0.42% P and $S_x$ = 0.01% P. Significance between treatment (gap distance) means is determined by the F-test. $S_x$, standard error of the sample mean; ns, not statistically significant (P>0.05).

ANOVA shows that there is no significant effect by area within plots for pepper P percent by dry weight (P=0.7844); for the left area, the mean P percent by dry weight is 0.43%; for the right area, the mean P percent by dry weight is 0.42%; and for the middle area, the mean P percent by dry weight is 0.42%. Furthermore, using orthogonal polynomial contrasts, no significant difference is found between the left and right areas versus the middle area (P=0.5320) for pepper P percent by dry weight. There is no interaction between gap and area (P=0.2866) for pepper P percent by dry weight.

For gap distance between panels, the variable of particular interest in this study, ANOVA shows that there is no significant effect on pepper P percent by dry weight (P=0.1304) (Figure 2.19). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, the mean P percent by dry weights are 0.42%, 0.44%, 0.41%, 0.42%, and 0.42%. Orthogonal polynomial contrasts show that the trend of pepper P percent by dry weight for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) does not fit a linear (P=0.4727) or a quadratic (P=0.2672) trend, but did fit cubic (P=0.0315) with increasing gap distance between panels. However, a cubic trend may not be indicative of an actual trend in the results. When contrasting the mean of the control plots (plants grown in the full sun) versus the mean of all of the AV plots (plants grown under the panels) there is no significant difference in pepper P percent by dry weight (P=.3462); the mean P percent by dry weight of the full sun control plots is 0.42% P and the mean P percent by dry weight of the AV plots is 0.43%.

### 2.3.7.3 Pepper Potassium

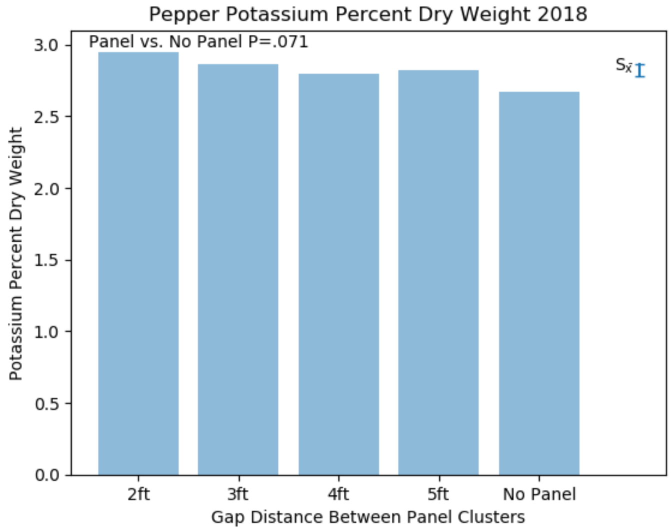


**Figure 2.20 Pepper Potassium Levels by Gap Distance Between Panels.**
The effect of gap distance between panels is not significant on pepper K percent by dry weight (P=0.2808). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, there are mean K percent by dry weights of 2.95%, 2.86%, 2.80%, 2.82%, and 2.67%, respectively. For the AV plots, there is no linear (P=0.2565), quadratic (P=0.5251), or cubic (P=0.9070) trend in pepper K percent by dry weight with increasing gap distance. Contrasts show there is a significant difference in pepper K percent by dry weight (P=0.0712) when comparing all of the AV plots with a mean of 2.86% K versus the control plots with a mean of 2.67% K (Panel vs. No Panel). Sample mean is 2.82% K and $S_{x=}$ 0.08% K. Significance between treatment (gap distance) means is determined by the F-test. $S_x$, standard error of the sample mean; *, statistically significant (P≤ 0.05); ns, not statistically significant (P>0.05).

ANOVA shows that there is no significant effect by area within plots for pepper K percent by dry weight (P=0.5850); for the left area, the mean K percent by dry weight is 2.87%; for the right area, the mean K percent by dry weight is 2.77%; and for the middle area, the mean K percent by dry weight is 2.82%. Furthermore, using orthogonal polynomial contrasts, no significant difference is found between the left and right areas versus the middle area (P=0.9908) for pepper K percent by dry weight. There is no interaction between gap and area (P=0.4592) for pepper K percent by dry weight.

For gap distance between panels, the variable of particular interest in this study, ANOVA shows that there is no significant effect on pepper K percent by dry weight (P=0.2808) (Figure 2.20). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, the mean K percent by dry weights are 2.95%, 2.86%, 2.80%, 2.82%, and 2.67%. Orthogonal polynomial contrasts show that the trend of pepper K percent by dry weight for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) does not fit a linear (P=0.2565), quadratic (P=0.5251), or cubic (P=0.9070) trend with increasing gap distance between panels. When contrasting the mean of the control plots (plants grown in the full sun) versus the mean of all of the AV plots (plants grown under the panels) there is a significant difference in pepper K percent by dry weight (P=.0712); the mean K percent by dry weight of the full sun control plots is 2.67% and the mean K percent by dry weight of the AV plots is 2.86%.

### 2.3.8 Broccoli Biomass Yields

#### 2.3.8.1 Broccoli Stem + Leaf Fresh Weight Per Plant

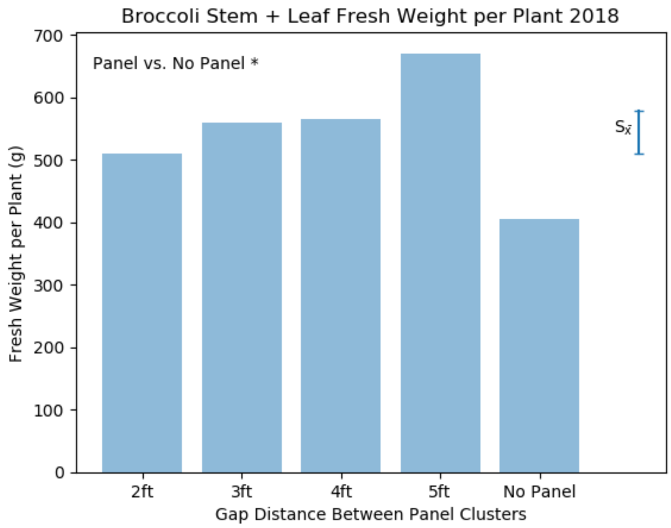


**Figure 2.21 Broccoli Stem + Leaf Fresh Weight Per Plant Yields by Gap Distance Between Panels.**
The effect of gap distance between panels is not significant on broccoli stem + leaf fresh weight per plant (P=.1410). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, there are mean broccoli stem + leaf fresh weights per plant of 510 g, 590 g, 564 g, 670 g, and 405 g respectively. For the AV plots, there is no linear (P=0.2855), quadratic (P=0.5767), or cubic (P=0.7205) trend in broccoli stem + leaf fresh weight yields per plant with increasing gap distance. Contrasts show there is a significant difference in stem + leaf fresh weight per plant (P=.0406) when comparing all of the AV plots with a mean fresh weight per plant of 588 g versus the control plots with a mean fresh weight per plant of 405 g (Panel vs. No Panel). Sample mean is 544 g per plant and $S_x$ = 69 g per plant. Significance between treatments (gap distance) means is determined by the F-test. $S_x$, standard error of the sample mean; *, statistically significant ($P \leq 0.05$); ns, not statistically significant ($P>0.05$).

ANOVA shows that there is no significant effect by area within plots for broccoli stem + leaf fresh weight per plant (P=9372); for the left area, the mean stem + leaf fresh weight per plant is 547 g; for the right area, the mean stem + leaf fresh weight per plant is 552 g; and for the middle area, the mean stem + leaf fresh weight per plant is 532 g. Specifically, using orthogonal polynomial contrasts, no significant difference is found between the left and right areas versus the middle area (P=.7965) for broccoli stem + leaf fresh weight per plant. There is no interaction between gap and area (P=.7763) for broccoli stem + leaf fresh weight per plant.

For gap distance between panels, the variable of particular interest in this study, ANOVA shows that there is no significant effect on broccoli stem + leaf fresh weight per plant yields (P=.1410) (Figure 2.21). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, the mean stem + leaf fresh weights per plant are 510 g, 560 g, 564 g, 670 g, and 405 g. Orthogonal polynomial contrasts show that the trend of broccoli stem + leaf fresh weight per plant for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) does not fit a linear (P=.2855), quadratic (P=.5767), or cubic (P=.7205) trend with increasing gap distance between panels. When contrasting the mean of the control plots (plants grown in the full sun) versus the mean of the AV plots (plants grown under the panels), there is a significant difference found in broccoli stem + leaf fresh weight per plant (P=.0406); the mean fresh weight per plant for the control plots is 405 g and the mean fresh weight per plant for the AV plots is 588 g. Overall, broccoli stem fresh weights per plant for the 2-ft, 3-ft, 4-ft, or 5-ft plots are 126%, 138%, 139%, and 165% of the control yield.

### 2.3.8.2 Broccoli Stem + Leaf Dry Weight Per Plant

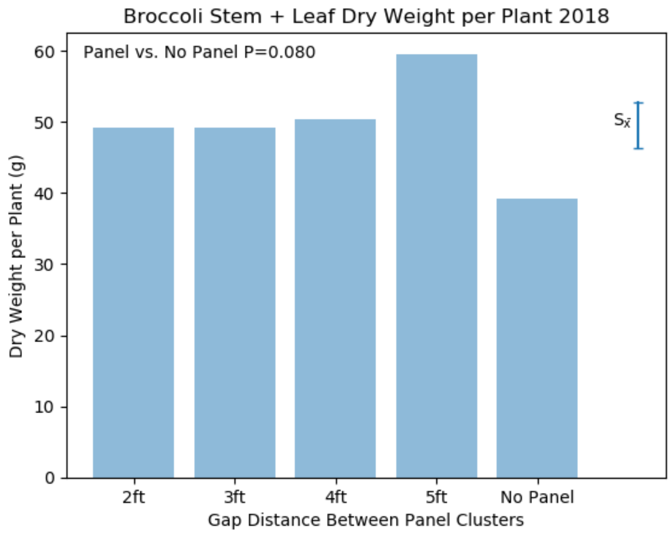


**Figure 2.22 Broccoli Stem + Leaf Dry Weight Per Plant Yields by Gap Distance Between Panels.**
The effect of gap distance between panels is not significant on broccoli stem + leaf dry weight per plant (P=.2723). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, there are mean broccoli stem + leaf dry weights per plant of 49 g, 49 g, 50 g, 60 g, and 39 g respectively. For the AV plots, there is no linear (P=.4887), quadratic (P=.4204), or cubic (P=.9522) trend in broccoli stem + leaf dry weight per plant with increasing gap distance. Contrasts show there is a significant difference in stem + leaf dry weight per plant (P=.0795) when comparing all of the AV plots with a mean dry weight per plant of 53 g versus the control plots with a mean dry weight per plant of 39 g (Panel vs. No Panel). Sample mean is 50 g per plant and $S_x$ = 6 g per plant. Significance between treatments (gap distance) means is determined by the F-test. $S_x$, standard error of the mean; *, statistically significant (P≤ 0.05); ns, not statistically significant (P>0.05).

ANOVA shows that there is no significant effect by area within plots for broccoli stem + leaf dry weight per plant (P=.9625); for the left are, the mean stem + leaf dry weight per plant is 49g; for the right area, the mean stem + leaf dry weight per plant is 50 g; and for the middle area, the mean stem + leaf dry weight per plant is 49 g. Specifically, using orthogonal polynomial contrasts, no significant difference is found between the left and right areas versus the middle area (P=.9738) for broccoli stem + leaf dry weight per plant. There is no interaction found between gap and area (P=.7959) for broccoli stem + leaf dry weight per plant.

For gap distance between panels, the variable of particular interest in this study, ANOVA shows that there is no significant effect on broccoli stem + leaf dry weight per plant yields (P=.2723) (Figure 2.22). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, the mean stem + leaf dry weights per plant are: 49 g, 49 g, 50 g, 60 g, and 39 g. Orthogonal polynomial contrasts show that the trend of broccoli stem + leaf dry weight per plant for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) does not fit a linear (P=0.4887), quadratic (P=0.4204), or cubic (P=0.9522) trend with increasing gap distance between panels. When contrasting the mean of the control plots (plants grown in the full sun) versus the mean of the AV plots (plants grown under the panels), there is a significant difference found in broccoli stem + leaf dry weight per plant (P=.0795); the mean dry weight per plant for the control plots is 39 g and the mean dry weight per plant for the AV plots is 53 g. Broccoli stem + leaf dry weights per plant for the 2-ft, 3-ft, 4-ft, and 5-ft plots are 126%, 125%, 129%, or 152% of the control yield.

### 2.3.8.3 Broccoli Flower Head Fresh Weight Per Plant

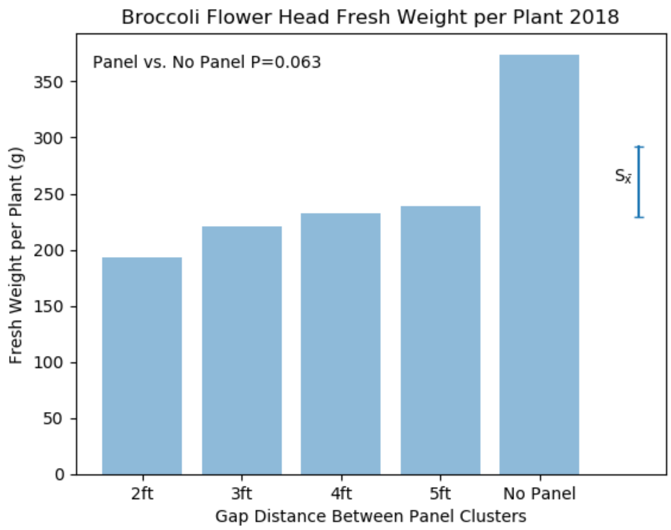


**Figure 2.23 Broccoli Flower Head Fresh Weight Per Plant Yields by Gap Distance Between Panels.**
The effect of gap distance between panels is not significant on broccoli flower head fresh weight per plant (P=.3772). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, there are mean broccoli flower head fresh weights per plant of 193 g, 221 g, 233 g, 239 g, and 374 g respectively. For the AV plots, there is no linear (P=.7588), quadratic (P=.9346), or cubic (P=.9054) trend in broccoli flower head fresh weight per plant with increasing gap distance. Contrasts show there is a significant difference in flower head fresh weight per plant (P=.0626) when comparing all of the AV plots with a mean flower head fresh weight per plant of 225 g versus the control plots with a mean flower head fresh weight per plant of 374 g (Panel vs. No Panel). Sample mean is 261 g per plant and $S_x$ = 63 g per plant. Significance between treatment (gap distance) means is determined by the F-test. $S_x$, standard error of the sample mean; *, statistically significant (P≤0.05); ns, not statistically significant (P>0.05).

ANOVA shows that there is no significant effect by area within plots for broccoli flower head fresh weight per plant (P=.8065); for the left area, the mean flower head fresh weight per plant is 278 g; for the right area,  the mean flower head fresh weight per plant is 273 g; and for the middle area,  the mean flower head fresh weight per plant 229 g. Specifically, using orthogonal polynomial contrasts, no significant difference is found between the left and right areas versus the middle area (P=.5579) for broccoli flower head fresh weight per plant. There is no interaction found between gap and area (P=.8099) for broccoli flower head fresh weight per plant.

For gap distance between panels, the variable of particular interest in this study, ANOVA shows that there is no significant effect (P=.3772) on broccoli flower head fresh weight per plant yields (Figure 2.23). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, the mean broccoli head fresh weights per plant are 193 g, 221 g, 233 g, 239 g, and 374 g. Orthogonal polynomial contrasts show that the trend of broccoli flower head fresh weight per plant for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) does not fit a linear (P=0.7588), quadratic (P=.9346), or cubic (P=.9054) trend with increasing gap distance between panels. When contrasting the mean of the control plots (plants grown in the full sun) versus the mean of the AV plots (plants grown under the panels), there is a significant difference found in broccoli flower head fresh weight per plant (P=.0626); the mean fresh weight per plant of the control plots is 374 g and the mean fresh weight per plant for the AV plots is 225 g. Broccoli flower head fresh weights per plant for the 2-ft, 3-ft, 4-ft, and 5-ft plots are 52%, 59%, 62%, and 64% of the control yield.

### 2.3.8.4 Broccoli Flower Head Dry Weight Per Plant

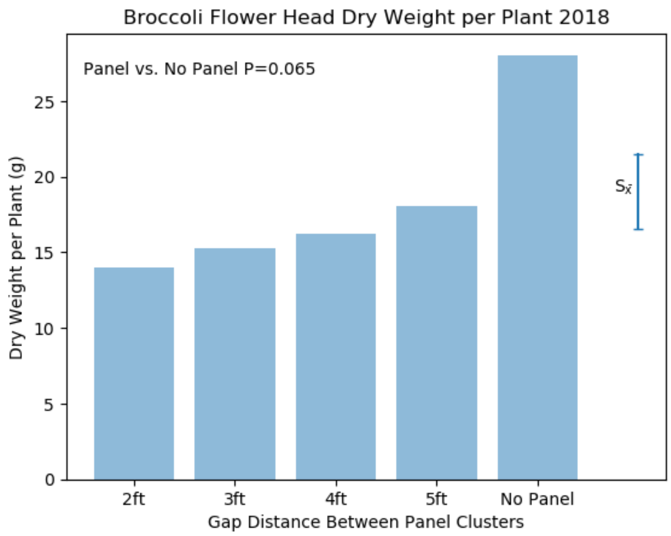


**Figure 2.24 Broccoli Flower Head Dry Weight Per Plant Yields by Gap Distance Between Panels.**
The effect of gap distance between panels is not significant on broccoli flower head dry weight per plant (P=.3702). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, there are mean broccoli flower head dry weights per plant of 14 g, 15 g, 16 g, 18 g, and 28 g respectively. For the AV plots, there is no linear (P=.7231), quadratic (P=.9418), or cubic (P=.8421) trend in broccoli flower head dry weight per plant with increasing gap distance. Contrasts show there is a significant difference in flower head dry weight per plant (P=.0646) when comparing all of the AV plots with a mean flower head dry weight per plant of 16 g versus the control plots with a mean flower head dry weight per plant of 28 g (Panel vs. No Panel). Sample mean is 19 g per plant and $S_x$ = 5 g per plant. Significance between treatment (gap distance) means is determined by the F-test. $S_x$, standard error of the sample mean; *, statistically significant ($P \leq 0.05$); ns, not statistically significant ($P>0.05$).

ANOVA show that there is no significant effect by area within plots for broccoli flower head dry weight per plant (P=.8087); for the left area, the mean flower head dry weight per plant is 20 g; for the right area, the mean flower head dry weight per plant is 20 g; and for the middle area, the mean flower head dry weight per plant is 17 g. Specifically, using orthogonal polynomial contrasts, no significant difference is found between the left and right areas versus the middle area for broccoli flower head dry weight per plant (P=.5950). There is no interaction found between gap and area for broccoli flower head dry weight per plant (P=.7985).

For gap distance between panels, the variable of particular interest in this study, ANOVA shows that there is no significant effect on broccoli flower head dry weight per plant yields (P=.3702) (Figure 2.24). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, the mean broccoli flower head dry weights per plant are 14 g, 15 g, 16 g, 18 g, and 28 g. Orthogonal polynomial contrasts show that the trend of broccoli flower head dry weight per plant for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) does not fit a linear (P=.7231), quadratic (P=.9418), or cubic (P=.8421) trend with increasing gap distance. When contrasting the mean of the control plots (plants grown in the full sun) versus the mean of the AV plots (plants grown under the panels), there is a significant difference found in broccoli flower head dry weight per plant (P=.0646); the mean dry weight per plant for the control plots is 28 g and the mean dry weight per plant for the AV plots is 16 g. Broccoli flower head dry weights per plant for the 2-ft, 3-ft, 4-ft, or 5-ft plots are 50%, 55%, 58%, and 64% of the control yield.

### 2.3.9 Broccoli Nutrient Levels

#### 2.3.9.1 Broccoli Nitrogen

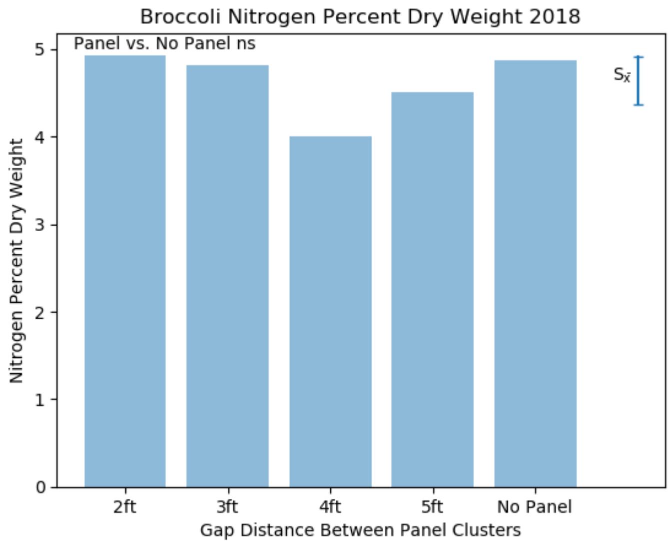


**Figure 2.25 Broccoli Nitrogen Levels by Gap Distance Between Panels.**
The effect of gap distance between panels is not significant on broccoli N percent by dry weight (P=.9571). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, there are mean N percent by dry weights of 4.93%, 4.81%, 4.00%, 4.51%, and 4.87% respectively. For the AV plots, there is no linear (P=.6431), quadratic (P=.9079), or cubic (P=.7066) trend in broccoli N percent by dry weight with increasing gap distance. Contrasts show there is not a significant difference in broccoli N percent by dry weight (P=.6790) when comparing all of the AV plots with a mean of 4.56% N versus the control plots with a mean of 4.87% N (Panel vs. No Panel). Sample mean is 4.64% N and $S_x$ = 0.54% N. Significance between treatment (gap distance) means is determined by the F-test. $S_x$, standard error of the sample mean; ns, not statistically significant (P>0.05).

ANOVA shows that there is no significant effect by area within plots for broccoli N percent by dry weight (P=.5053); for the left area, the mean N percent by dry weight is 4.58%; for the right area, the mean N percent by dry weight is 4.34%; and for the middle area, the mean N percent by dry weight is 5.03%. Specifically, using orthogonal polynomial contrasts, no significant difference is found between the left and right areas versus the middle area for broccoli N percent by dry weight (P=.2779). There is no interaction found between gap and area for broccoli N percent by dry weight (P=.8199).

For gap distance between panels, the variable of particular interest in this study, ANOVA shows that there is no significant effect on broccoli N percent by dry weight (P=.9571) (Figure 2.25). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, the mean N percent by dry weights are 4.93%, 4.81%, 4.00%, 4.51%, and 4.87%. Orthogonal polynomial contrasts show that the trend of broccoli N percent by dry weight for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) does not fit a linear (P=.6431), quadratic (P=.9079), or cubic (P=.7066) trend with increasing gap distance between panels. When contrasting the mean of the control plots (plants grown in the full sun) versus the mean of all of the AV plots (plants grown under the panels) there is no significant difference in broccoli N percent by dry weight (P=.6790); the mean N percent by dry weight of the full sun control plots is 4.87% and the mean N percent by dry weight of the AV plots is 4.56%.

### 2.3.9.2 Broccoli Phosphorus

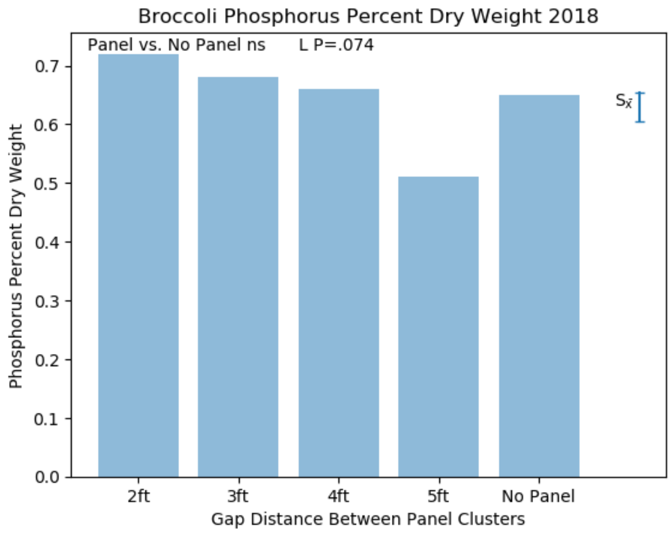


**Figure 2.26 Broccoli Phosphorus Levels by Gap Distance Between Panels.** The effect of gap distance between panels is not significant on broccoli P percent by dry weight (P=.1419). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, there are mean P percent by dry weights of 0.72%,0 .68%, 0.66%, 0.51%, and 0 .65% respectively. For the AV plots, there is a linear (P=.0736) trend and no quadratic (P=.1739) or cubic (P=.6681) trend in broccoli P percent by dry weight with increasing gap distance. Contrasts show there is not a significant difference in broccoli P percent by dry weight (P=.8033) when comparing all of the AV plots with a mean of 0.63% P versus the control plots with a mean of 0.65% P (Panel vs. No Panel). Sample mean is 0.63% P and $S_x$ = .05% P. Significance between treatment (gap distance) means is determined by the F-test. L, Linear; $S_x$, standard error of the sample mean; *, statistically significant (P≤ 0.05); ns, not statistically significant (P>0.05).

ANOVA shows that there is no significant effect by area within plots for broccoli P percent by dry weight (P=.3938); for the left area, the mean P percent by dry weight is 0.61%; for the right area, the mean P percent by dry weight is 0.61%; and for the middle area, the mean P percent by dry weight is 0.69%. Specifically, using orthogonal polynomial contrasts, no significant difference is found between the left and right areas versus the middle area for broccoli P percent by dry weight (P=.1844). There is no interaction found between gap and area for broccoli P percent by dry weight (P=.8135).

For gap distance between panels, the variable of particular interest in this study, ANOVA shows there is no significant effect on broccoli P percent by dry weight (P=.1419) (Figure 2.26). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, the mean P percent by dry weights are 0.72%, 0.68%, 0.66%, 0.51%, and 0.65%. Orthogonal polynomial contrasts show that the trend of broccoli P percent by dry weight for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) does fit a linear (P=.0736) trend and not a quadratic (P=.1739) or cubic (P=.6681) trend with increasing gap distance between panels. When contrasting the mean of the control plots (plants grown in the full sun) versus the mean of all of the AV plots (plants grown under the panels) there is no significant difference in broccoli P percent by dry weight (P=.8033); the mean P percent by dry weight of the full sun control plots is 0.65% and the mean P percent by dry weight of the AV plots is 0.63%.

### 2.3.9.3 Broccoli Potassium

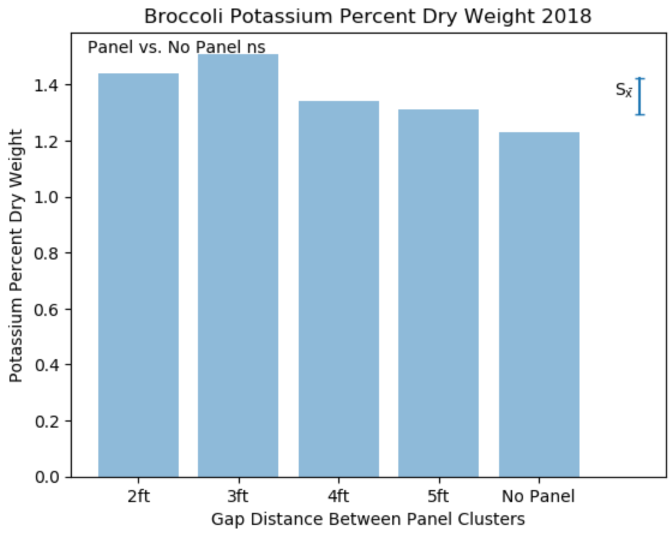


**Figure 2.27 Broccoli Potassium Levels by Gap Distance Between Panels.** The effect of gap distance between panels is not significant on broccoli K percent by dry weight (P=.5767). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, there are K percent by dry weights of 1.44%, 1.51%, 1.34%, 1.31%, and 1.23% respectively. For the AV plots, there is no linear (P=.6837), quadratic (P=.6265), or cubic (P=.3366) trend in broccoli K percent by dry weight with increasing gap distance. Contrasts show there is not a significant difference in broccoli K percent by dry weight (P=.3790) when comparing all of the AV plots with a mean of 1.40% K versus the control plots with a mean of 1.22% K (Panel vs. No Panel). Sample mean is 1.36% K and $S_x$ = 0.13% K. Significance between treatment (gap distance) means is determined by the F-test. $S_x$, standard error of the sample mean; ns, not statistically significant (P>0.05).

ANOVA shows that there is no significant effect by area within plots for broccoli K percent by dry weight (P=.7626); for the left area, the mean K percent by dry weight is 1.36%; for the right area, the mean K percent by dry weight is 1.40%; and for the middle area, the mean K percent by dry weight is 1.31%. Specifically, using orthogonal polynomial contrasts, no significant difference is found between the left and right areas versus the middle area for broccoli K percent by dry weight (P=.5427). There is no interaction found between gap and area for broccoli K percent by dry weight (P=.8171).

For gap distance between panels, the variable of particular interest in this study, ANOVA shows there is no significant effect on broccoli K percent by dry weight

(P=.5767) (Figure 2.27). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, the mean K percent by dry weights are 1.44%, 1.51%, 1.34%, 1.31%, and 1.23%. Orthogonal polynomial contrasts show that the trend of broccoli K percent by dry weight for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) does not fit a linear (P=.6837), quadratic (P=.6265), or cubic (P=.3366) trend with increasing gap distance between panels. When contrasting the mean of the control plots (plants grown in the full sun) versus the mean of all of the AV plots (plants grown under the panels) there is no significant difference in broccoli K percent by dry weight (P=.3790); the mean K percent by dry weight of the full sun control plots is 1.22% and the mean K percent by dry weight of the AV plots is 1.40%.

### 2.3.10 Soil Water Content

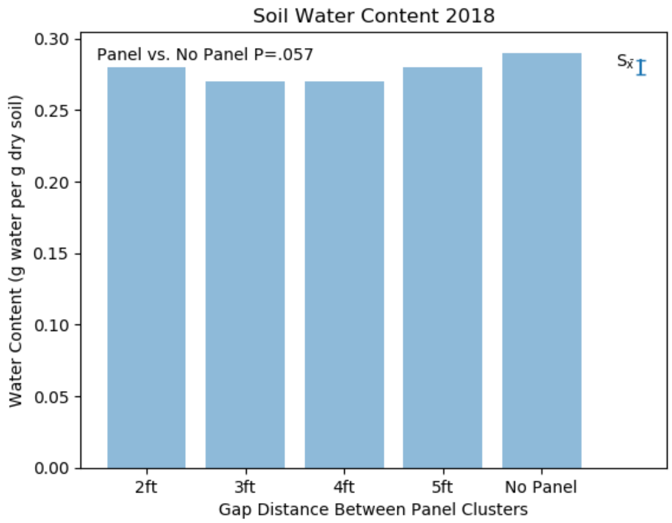


**Figure 2.28 Soil Water Content by Gap Distance Between Panels.**
The effect of gap distance between panels is not significant on soil water content (P=.1738). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel there are mean soil water contents of 0.29 g, 0.27 g, 0.27 g, 0.28 g, and 0.29 g water per g dry soil respectively. For the AV plots, there is no linear (P=.4574), quadratic (P=.1489), or cubic (P=.7228) trend in soil water content with increasing gap distance. Contrasts show there is a significant difference in soil water content (P=.0570) when comparing all of the AV plots with a mean of 0.28 g water per g dry soil versus the control plots with a mean of 0.29 g water per g dry soil (Panel vs. No Panel). Sample mean is 0.28 g of water per g dry soil and $S_x = 0.01$ g of water per g dry soil. Significance between treatment (gap distance) means is determined by the F-test. $S_x$, standard error of the sample mean;*, statistically significant (P≤ 0.05); ns, not statistically significant (P>0.05).

ANOVA shows that there is no significant effect by area within plots for soil water content (P=.8776); each left, right, and middle area had a mean soil water content of 0.28 g of water per g of dry soil. Specifically, using orthogonal polynomial contrasts, no significant difference is found between the left and right areas versus the middle area for soil water content (P=.6279).

For gap distance between panels, the variable of particular interest in this study, ANOVA shows that there is no significant effect on soil water content (P=.1738) (Figure 2.28). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, the mean soil water contents are 0.28 g, 0.27 g, 0.27 g, 0.28 g, and 0.29 g of water per g dry soil. Furthermore, orthogonal polynomial contrasts show that the trend of soil water content for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) does not fit a linear (P=.4574), quadratic (P=.1489), or cubic (P=.7228) trend with increasing gap distance. When contrasting the mean of the control plots (in the full sun) versus the mean of all of the AV plots (under the panels), there is a significant difference found in soil water content (P=.0570); the mean soil water content in the control plots is 0.29 g of water per g of dry soil and the mean soil water content in the AV plots is 0.28 g of water per g of dry soil. Interestingly, although the effects of gap or area alone are not significant on soil water content, there is a significant interaction found between gap and area within the experimental plots (P=.0005).

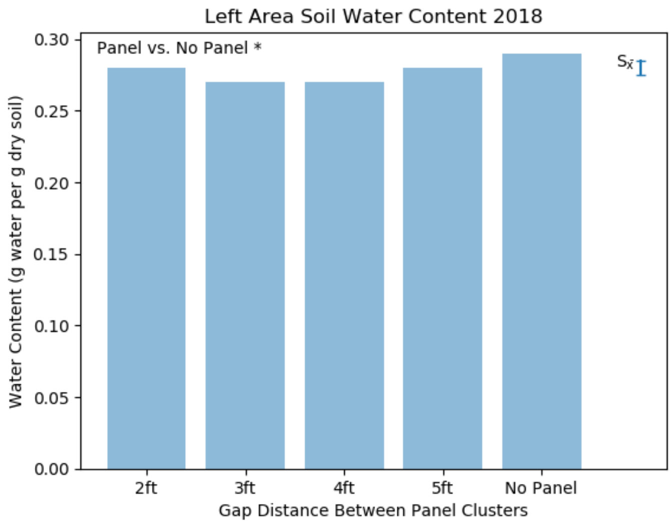


**Figure 2.29 Left Area Soil Water Content by Gap Distance Between Panels**
For soil water content the interaction effect of gap x area is significant (P=.0005). Specifically, separating the interaction by area shows that gap does not have a significant effect on soil water content in the first (left area) (P=.4554). For the left area, the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel there are mean soil water contents of 0.28 g, 0.27 g, 0.27 g, 0.28 g, and 0.29 g water per g dry soil respectively. For the left areas of the AV plots, there is no linear (P=.9816), quadratic (P=.0932), or cubic (P=.8787) trend in soil water content with increasing gap distance. Contrasts show there is a significant difference in soil water content (P=.0219) when comparing all of the AV plots left areas with a mean of 0.28 g of water per g of dry soil versus the control plots left areas with a mean of 0.29 g of water per g of dry soil (Panel vs. No Panel). Sample mean is 0.28g of water per g of dry soil and $S_x$ = 0.01 g of water per g of dry soil. Significance between treatment (gap distance) means is determined by the F-test. $S_x$, standard error of the mean; *, statistically significant (P≤0.05); ns, not statistically significant (P>0.05).

Separating the interaction of gap x area by area (using least square means), because we are most interested in gap distance effect, shows that the gap variable does not have a significant effect on soil water content in the left area of the experimental plots (P=.4554) (Figure 2.29). Specifically, for the left area (where gap distance does not have a significant effect) of the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, there are mean soil water contents of 0.28 g, 0.27 g, 0.27 g, 0.28 g, and 0.29 g water per g dry soil respectively (Figure 2.29). Furthermore, orthogonal polynomial contrasts show that the trend of soil water content for the left areas of the AV plots there is no linear (P=.9816), quadratic (P=.0932) or cubic trend (P=.8787) trend with increasing gap distance between panels. However, when contrasting the mean of the left areas of the control plots (in the full sun) versus the mean of all of the left areas of the AV plots (under the panels), there is a significant difference found in soil water content (P=.0219); the mean soil water content in the right areas of the control plots is 0.29 g of water per g of dry soil and the mean soil water content in the right areas of the AV plots is 0.28 g of water per g of dry soil.

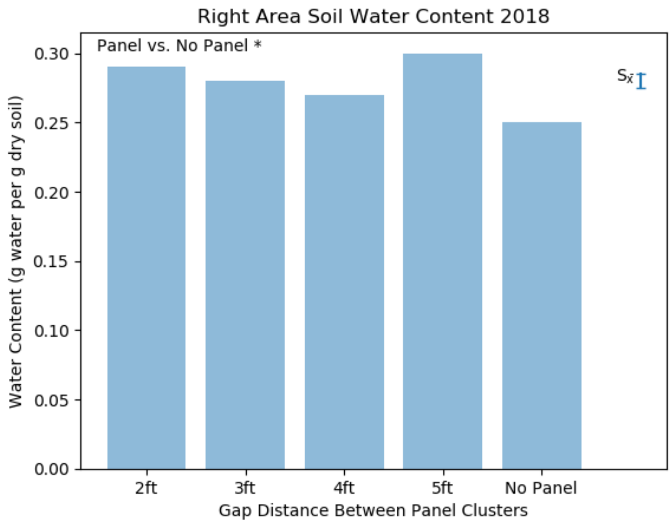


**Figure 2.30 Right Area Soil Water Content by Gap Distance Between Panels.** For soil water content the interaction effect of gap x area is significant (P=.0005). Specifically, separating the interaction by area shows that gap does have a significant effect on soil water content in the second (right area) (P=.0396). For the right area, the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel there are mean soil water contents of 0.29 g, 0.28 g, 0.27 g, 0.30 g, and 0.25 g water per g dry soil respectively. For the right areas of the AV plots, there is no linear (P=.7245), quadratic (P=.1484), or cubic (P=.2310) trend in soil water content with increasing gap distance. Contrasts show there is a significant difference in soil water content (P=.0196) when comparing all of the AV plots right areas with a mean of 0.28 g of water per g of dry soil versus the control plots right areas with a mean of 0.25 g of water per g of dry soil (Panel vs. No Panel). Sample mean is 0.28 g of water per g of dry soil and $S_x$ = 0.01 g of water per g of dry soil. Significance between treatment (gap distance) means is determined by the F-test. $S_x$, standard error of the mean; *, statistically significant ($P \leq 0.05$); ns, not statistically significant ($P>0.05$).

Separating the interaction of gap x area by area (using least square means), because we are most interested in gap distance effect, shows that the gap variable does have a significant effect on soil water content in the right areas of the experimental plots (P=.0396) (Figure 2.30). Specifically, for the right areas (where gap distance does have a significant effect) of the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, there are mean soil water contents of 0.29 g, 0.28 g, 0.27 g, 0.30 g, and 0.25 g water per g dry soil respectively (Figure 2.30). Furthermore, orthogonal polynomial contrasts show that the trend of soil water content for the right areas of the AV plots there is no linear (P=.7245), quadratic (P=.1484) or cubic trend (P=.2310) with increasing gap distance between panels. When contrasting the mean of the right areas of the control plots (in the full sun) versus the mean of all of the right areas of the AV plots (under the panels), there is a significant difference found in soil water content (P=.0196); the mean soil water content in the right area of the control plots is 0.25 g of water per g of dry soil and the mean soil water content in the right areas of the AV plots is 0.28 g of water per g of dry soil.

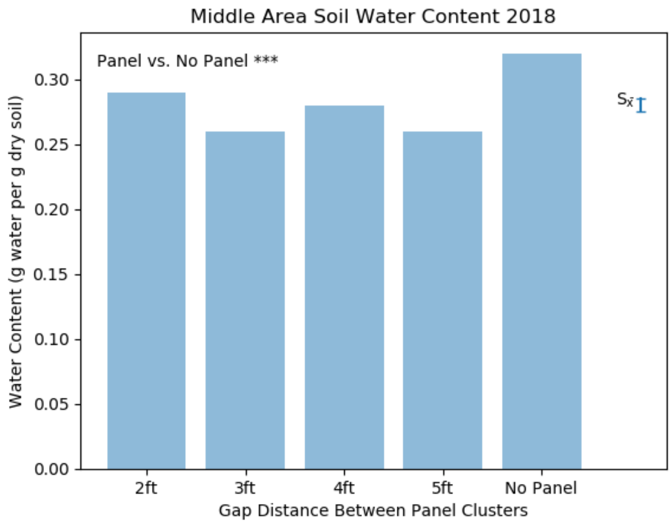


**Figure 2.31 Middle Area Soil Water Content by Gap Distance Between Panels.** For soil water content the interaction effect of gap x area is significant (P=.0005). Specifically, separating the interaction by area shows that gap does have a significant effect on soil water content in the third (middle area) (P=.0002). For the middle area, the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel there are mean soil water contents of 0.29 g, 0.26 g, 0.28 g, 0.26 g, and 0.32 g water per g dry soil respectively. For the middle areas of the AV plots, there is no linear (P=.1216), quadratic (P=.9239), or cubic (P=.0968) trend in soil water content with increasing gap distance. Contrasts show there is a significant difference in soil water content (P=.0003) when comparing all of the AV plots middle areas with a mean of 0.27 g of water per g of dry soil versus the control plots middle areas with a mean of 0.32 g of water per g of dry soil (Panel vs. No Panel). Sample mean is 0.28 g of water per g of dry soil and $S_x$ = 0.01 g of water per g of dry soil. Significance between treatment (gap distance) means is determined by the F-test. $S_x$, standard error of the sample mean; ***, statistically significant (P≤0.001); ns, not statistically significant (P>0.05).

Separating the interaction of gap x area by area (using least square means), because we are most interested in gap distance effect, shows that the gap variable does have significant effect on soil water content in the middle areas of the experimental plots (P=.0002) (Figure 2.31). Specifically, for the middle areas (where gap distance does have a significant effect) of the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, there are mean soil water contents of 0.29 g, 0.26 g, 0.28 g, 0.26 g, and 0.32 g water per g of dry soil respectively (Figure 2.31). Furthermore, orthogonal polynomial contrasts show that the trend of soil water content for the middle areas of the AV plots there is no linear ($P=.1216$), quadratic ($P=.9239$) or cubic trend ($P=.0968$) with increasing gap distance between panels. When contrasting the mean of the right areas of the control plots (in the full sun) versus the mean of all of the right areas of the AV plots (under the panels), there is a significant difference found in soil water content ($P=.0003$); the mean soil water content in the middle area of the control plots is 0.32 g of water per g of dry soil and the mean soil water content in the middle areas of the AV plots is 0.27 g of water per g of dry soil.

### 2.3.11 Leaf Temperature

#### 2.3.11.1 Sunny days

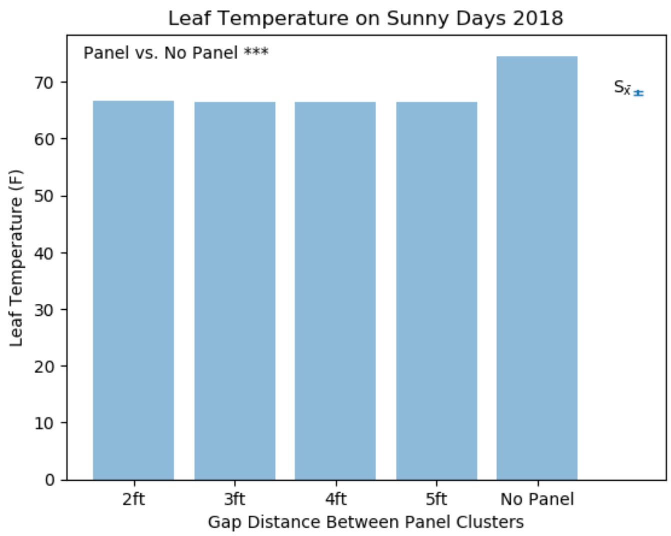


**Figure 2.32 Pepper Leaf Temperature on Sunny Days by Gap Distance Between Panels.**
The effect of gap distance between panels is significant on pepper leaf temperatures (˚F) on sunny days (P<.0001). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, there are mean leaf temperatures of 67, 66, 66, 66, and 75 (˚F) respectively. For the AV plots, there is no linear (P=.8584), quadratic (P=.8877), or cubic (P=.8584) trend in pepper leaf temperature with increasing gap distance. Contrasts show there is a significant difference in pepper leaf temperatures on sunny days (P<.0001) when comparing all of the AV plots with a mean of 66 (˚F) versus the control plots with a mean of 75 (˚F) (Panel vs. No Panel). Sample mean is 68 (˚F) and $S_x = 1$ (˚F). Significance between treatment (gap distance) means is determined by the F-test. $S_x$ , standard error of the sample mean; **, statistically significant (P≤0.01); ns, not statistically significant (P>0.05).

ANOVA shows that there is a significant effect by time (P<.0001) on pepper leaf temperature on sunny days. For the different times the samples were taken 9am, 12pm, and 3pm the temperatures are 66, 67, and 71 (˚F). Specifically, using orthogonal polynomial contrasts, on sunny days no significant difference is found between the 9am and 12pm pepper leaf temperatures (P=.0758); while there is a significant difference found between the 9am and 3pm pepper leaf temperatures (P<.0001); and there is a significant difference found between the 12pm and 3pm pepper leaf temperatures ($P<.0001$). These variations show that pepper leaf temperatures vary throughout the day in the experimental plots. Lastly, ANOVA shows that there is no interaction between time and gap for pepper leaf temperature ($P=.9780$).

For gap distance between panels, the variable of particular interest in this study, ANOVA shows there is a significant effect on pepper leaf temperature on sunny days ($P<.0001$) (Figure 2.32). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, the mean pepper leaf temperatures are 67, 66, 66, 66, and 75 (°F) respectively. Orthogonal polynomial contrasts show that the trend of pepper leaf temperature on sunny days for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) does not fit a linear ($P=.8584$), quadratic ($P=.8877$), or cubic trend ($P=.8584$) with increasing gap distance between panels. When contrasting the mean of the control plots (plants grown in the full sun) versus the mean of all of the AV plots (plants grown under the panels) there is a significant difference in pepper leaf temperature on sunny days ($P<.0001$); the mean pepper leaf temperature in the full sun control plots is 75 (°F) and the mean pepper leaf temperature in the AV plots is 66 (°F). Ultimately, on sunny days, pepper leaf temperatures are lower in the shade of the panels but there is no trend in the AV plots as gap distance increases and shading decreases.

### 2.3.11.2 Cloudy days

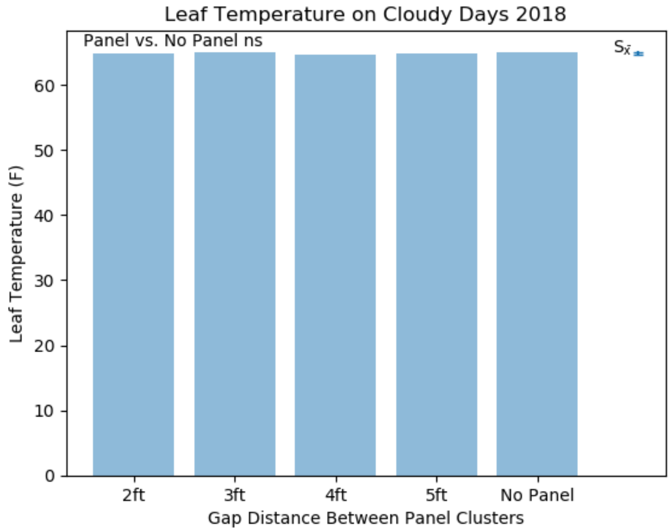


**Figure 2.33 Pepper Leaf Temperature on Cloudy Days by Gap Distance Between Panels.**
The effect of gap distance between panels is not significant on pepper leaf temperatures (°F) on cloudy days (P=.9498). For the experimental plots with gap distances of 2-ft, 3-ft, 4-ft, -ft, or no panel, there are mean leaf temperatures of 65 °F. For the AV plots, there is no linear (P=.6409), quadratic (P=.8516), or cubic (P=.6037) trend in pepper leaf temperature with increasing gap distance. Contrasts show there is not a significant difference in pepper leaf temperatures on cloudy days (P=.6727) when comparing all of the AV plots with a mean of 65 (°F) versus the control plots with a mean of 65 (°F) (Panel vs. No Panel). Sample mean is 65 (°F) and $S_x$ = 0.37 (°F). Significance between treatment (gap distance) means is determined by the F-test. $S_x$, standard error of the sample mean; ns, not statistically significant (P>0.05).

ANOVA shows that there is a significant effect by time (.0887) on pepper leaf temperature on cloudy days. For the different times the samples were taken 9am, 12pm, and 3pm the temperatures are 65, 64, and 65 (°F). Specifically, using orthogonal polynomial contrasts, on cloudy days there is a significant difference found between the 9am and 12pm pepper leaf temperatures (P=.0833); while there is not a significant difference found between the 9am and 3pm pepper leaf temperatures (P=7464); and there is a significant difference found between the 12pm and the 3pm pepper leaf temperatures (P=.0410). These variations show that pepper leaf temperatures vary throughout the day in the experimental plots. Lastly, ANOVA shows that there is no interaction between time and gap for pepper leaf temperature (P=.9764).

For gap distance between panels, the variable of particular interest in this study, ANOVA shows there is not a significant effect on pepper leaf temperature on cloudy days (P=.9498) (Figure 2.33). For the experimental plots with gaps of 2-ft, 3-ft, 4-ft, 5-ft, or no panel, the mean pepper leaf temperatures are all 65 (°F). Orthogonal polynomial contrasts show that the trend of pepper leaf temperature on cloudy days for the AV plots (2-ft, 3-ft, 4-ft, or 5-ft gaps) does not fit a linear (P=.6409), quadratic (P=.8516), or cubic trend (P=.6037) with increasing gap distance between panels. When contrasting the mean of the control plots (plant grown in the full sun) versus the mean of the AV plots (plants grown under the panels) there is no significant difference in pepper leaf temperature on cloudy days (P=.6727); the mean pepper leaf temperature in the full sun control plots is of 65 (°F) and the mean pepper leaf temperature in the AV plots is also 65 (°F). Ultimately, on cloudy days, pepper leaf temperatures do not differ in the shade of the panels compared to the pepper leaf temperatures without panel shading.

## 2.4 Discussion

### 2.4.1 Light Measurements

To confirm and quantify that there is a reduction in light under the panels compared to the full sun, light measurements are taken. The different gap distances allow for different amounts of light to reach the crops below the panels. The larger the gap distances, the more light is available; light percent of full sun at the crop level increases linearly from the 2-ft to the 5-ft gap distance AV plots.

Light is measured from one day at noon because it was measured manually. However, I would recommend that in future experiments it be taken in a variety of conditions and days and times to confirm the pattern of reduced light at the crop level and how light amounts change by area throughout the day. This knowledge is of particular interest because the sun changes positions throughout the day and because of this depending on the position of the sun different areas than the middle would be shaded and receive less light. Different areas would be shaded because the amount of sunlight on a surface is a result of the angle of incidence of the sun (Rizk and Chaiko, 2008). In the morning and in the evening, the sun hits the panels at about a 90 degree angle (Rizk and Chaiko, 2008). From morning to mid-day, the 90 degree angle approaches 0 so that the sun hits the panels perpendicularly at midday (Rizk and Chaiko, 2008). From midday to dusk, as the sun begins to set, the reverse occurs (Rizk and Chaiko, 2008). Consequently, because of the changing angle at which the sun hits the panels throughout the day light is able to penetrate the gaps between solar panels so that areas within plots under the panels (AV plots) receive similar amounts of light.

When the light measurement was taken in this experiment the sun was directly above the panel (perpendicular to the panel) and consequently the area directly below the panel (the middle area) was shaded and the left and right areas of the panels received light. As the sun changes position different areas below the panels in the AV plots are cast in the shadow of the panel. Ultimately because all areas in plots received shading at some point in the day no significant effect by area within plot is expected on crop biomass and nutrient yields. However, more data on light amounts at the crop level at different times of the day and on more days would have been beneficial to further demonstrate the degree of shading in the AV plots. Overall, the light measurement demonstrates that AV plots do experience a shifting reduction in light throughout the day compared to the full sun control plots and that smaller gap spacing distance between panel clusters decreases light penetration to crops in AV systems.

### 2.4.2 Crop Biomass Yields

The amount of light that a crop intercepts is a crucial determinant in plant growth and development (Campillo et al., 2012). In the photosynthetic process sunlight (solar radiation) is the energy source that plants use to convert $CO_2$ and water into organic compounds that are used to develop plant parts such as stems, roots, leaves, and fruits (Campillo et al., 2012). There are different factors that influence how much radiation a plant is able to intercept. Some such factors include the leaf angle of a plant, the leaf surface properties and how it reflects sunlight, the leaf thickness and chlorophyll concentration, leaf size and shape, leaf arrangement, sun elevation, and the distribution of solar radiation to the plant (shade or a reduction in solar radiation is of particular interest here) (Campillo et al., 2012). Production strategies to maximize biomass production are aimed at optimizing interception of solar radiation (Campillo et al., 2012). Specifically, the amount of dry matter produced by a crop is related directly to the amount of solar radiation it receives if there are no other stressing environmental conditions (Campillo et al., 2012). Consequently, a heavy shade of crops can cause a decline in plant biomass production because it decreases the amount of photosynthesis (Hamdani et al., 2018). However, when the correct amount of shading is used, biomass production can still remain quite high and, especially in heat-stress environments with high temperatures such as the tropics, shading can even increase biomass yields (Gent, 2008). Overall, it is accepted commonly that shading can reduce photosynthetic rates; however, when plants are near their maximum photosynthetic activity (most leaves are at the light saturation point), shade can actually benefit a plant where temperatures are too hot and cause damage to the plant by reducing incoming solar radiation (Parbst, 2010). In this experiment shading occurs at different levels in the AV experimental plots occurs because of solar panels which disrupt the interception of solar radiation by the plants below and potentially also potentially decrease yields.

Additionally, when considering crop yield in shading conditions, it must be considered that there is a large variation in plant responses to shade including changes in leaf and plant morphology, productivity, and physiology (Wolff and Coltman, 1990). With regard to physiology, there has been studies on chlorophyll a and chlorophyll b content in shaded plants and whether the content increases or decreases in shaded leaves. There has been conflicting research and results on this phenomenon; some results show that chlorophyll levels decrease as the shading density increases whereas others show that chlorophyll content increases with shading density (Fan et al., 2017). In general, it is thought that chlorophyll content increases in shaded plants (Diaz-Perez, 2013).

Crops perform differently in shaded conditions because of variation in their ability to adapt to shaded conditions. For example, certain lettuce varieties (a leafy vegetable) do not have limited growth in shade; in these cases the specific leaf area of the lettuce actually increases with percent shade showing that lettuce is a crop that is adapted or able to adapt to shading conditions (Wolff and Coltman, 1990). Diaz-Perez (2013) examined bell pepper (*Capsicum annum* L.) growth in 0%, 30%, 47%, 62%, and 89% shade and noted that the peppers were relatively shade tolerant and that moderate shading resulted in lower leaf temperature and transpiration but did not reduce overall biomass production (Diaz-Perez, 2013). However, for the same peppers plant height and leaf area increased with shade, but number of leaves and pepper fruit biomass decreased as shade increased. A common response in crops to shade is an increase in specific leaf area; however, a decline in vegetative biomass occurs (Gent, 2008). For example, Gent (2008) observed that tomatoes (*Lycopersicon esculentum Mill. cv. Maofen*) were grown in shade in a greenhouse had increased leaf area but less vegetative biomass than ones in full sun. Additionally, a 2007 study of 'Legacy' broccoli (*brassica oleracea*) examined the growth of broccoli in shaded conditions (0, 35, and 70% shade) in a greenhouse (Franscengenali et al., 2007). The study found that with shading, broccoli above ground (leaves + stems) biomass increased and classified broccoli as a shade-tolerant crop because of its increase in leaf area to increase photosynthesis in shaded conditions and that commercial fresh weights decreased only at 70% shading in the greenhouse.

Plants are able to adjust their morphological and physiological functions in leaves to best suit their environmental conditions, but different plants vary in their shade tolerance (Lin et al., 1999). Consequently, considering a specific ability of a crop to adapt to shade and different levels of shade, we analyzed the results of Swiss chard, kale, peppers, and broccoli grown in our AV systems.

Considering all of the Swiss chard biomass yields in the AV plots they all have significantly reduced yields compared to the control. Within the AV plots, however, there did not appear to be a trend in the yields with differing levels of shade due differences in gap distance; so, the specific levels of shade do not have much of an effect on the yields. The suppression in yields in the AV plots is most likely as a consequence of reduced solar radiation leading to reduced photosynthesis.

Considering the kale biomass yields in the AV plots, they all have significantly reduced yields compared to the control plot. Within the AV plots, however, there appears to be a linear decline in the yields with differing levels of shade due differences in gap distance; with increasing gap distance between panels, the AV plots yields are more most likely due to reduced shading that allowed progressively more solar radiation to the AV plots. The 4-ft and 5-ft gap AV plots perform the best of the AV plots. The lower yields in the AV plots, again, is most likely as a consequence of reduced solar radiation leading to reduced photosynthesis.

Considering the pepper biomass yields in the AV plots, they all have significantly reduced yields compared to the control. Within the AV plots, however, there is no significant trend in the yields with differing levels of shade; so the specific levels of shade do not have as much of an effect on the yields. The limitation in pepper yields in the AV plots is most likely as a consequence of reduced solar radiation leading to reduced photosynthesis.

Considering the broccoli biomass yields for the stems and leaves in the AV plots, the trend in yields is to increase with decreased shade (increasing gap distance between panels) which was most likely due to reduced shading that allowed progressively more radiation to the AV plots. However, the control plots do not have as high broccoli yields as the AV plots which could be explained by the 5-ft gap plots providing an optimal amount of solar radiation for growth whereas the control plots may have had more heat stress as was mentioned in Gent (2008). Additionally, it is possible that in response to shading plant resources were allocated away from production of the broccoli flower heads and to the production of leaves and stems to increase light capture through photosynthesis (Wolff and Coltman, 1990).

The broccoli flower head biomass yields in the AV plots are significantly different in yields from the control plots yields, but there does appear to be a trend in that yields increase with a decrease in shade. However, compared to the stem + leaf biomass yields where the control plots produced less, for the flower head biomass yield the control plots produced the most. The larger flower head weights in the control plots is most likely because there is not a reduction in radiation so energy and plants can be focused on producing the flower (head) of the broccoli whereas with increased shade, energy is focused on increasing leaf biomass (Wolff and Coltman, 1990).

Overall, the biomass production of the four crops for their harvestable parts is lower in the AV plots than in the full-sun control plots. This phenomenon can be attributed to a reduction in radiation reaching the crops. Pepper appears to be most affected by shade as a fruiting crop. Seidlova (2008) suggested fruiting crops are more susceptible to shade stress than leafy vegetables. Swiss chard and kale seem to be affected moderately by shaded conditions. Either Swiss chard or kale have a significant difference by gap distance in at least fresh and dry weight biomasses; the control plots have higher Swiss chard yields and kale yields than the other plots. However, unlike Swiss chard, kale yields increase with a decrease in shade. It is expected that as leafy vegetables, Swiss chard and kale would perform better than fruit crops in shade (Seidlova et al., 2008). Interestingly, for either Swiss chard or kale, leaf number per plant in the experimental plots are high and for Swiss chard there is not a significant difference between leaf number of the AV plots and leaf number of the control plots. This result indicates that leaf initiation and leaf number are not limited as much as overall growth. Broccoli, which has a flower head as the edible part surrounded by leaves, seems to have performed the best in the shade; there is a significant difference in the stem + leaf biomass yields by gap distance between the AV plots and the control plots. Interestingly, broccoli stem + leaf weights are higher in the AV plots than in the control plots which indicates that resources may have been allocated to them to increase photosynthetic capacity of the plant in the shaded AV plots. The broccoli flower head weights are higher in the control plots and generally increase with a decrease in shade. This finding of broccoli as a shade tolerant crop is also found in a Franscengenali et al.( 2007) study that examined 'Legacy' broccoli (*brassica oleracea*) in shaded conditions and found, similar to our study, that with shading broccoli above ground (leaves and stems) biomass increases and classified broccoli a shade-tolerant crop because of its increase in leaf area to increase photosynthesis in shaded conditions.

Ultimately, based on the biomass results of crops grown under the solar panels, we recommend that for the use and implementation of AV systems, it is essential to understand what crops, especially by region, perform well in shade. For instance, certain fruiting crops like pepper or tomatoes in some climates can be injured by too much radiation (Diaz-Perez, 2013; Gent, 2008), and shade would be benefit crops in these areas. This experiment shows that all crops had higher yields in the control plots but that of the AV plots based on kale and broccoli, the 4-ft or 5-ft gap distance between panels is optimal.

### 2.4.3 Crop Nutrient Levels

The amount of solar radiation that a crop intercepts or the level of shading it receives has been shown to be influential in nutrient composition in plants. The general trend that has been recognized so far is that shading increases nutrient levels in the leaves of plants, specifically N, P, and K (Gent, 2008). For example, in several studies (Blair et al., 1983, Burridge et al., 1965, Diaz-Perez, 2013, Gent 2008, Liu et al., and Tindall, 1990) found that shading increases foliar concentrations of N, P, and K. One might expect that this result has to do with the decrease in size of a plant in the shade; however, a review by Craine et al. 2013 reported that nutrient uptake is proportional to the root length of crops; larger roots acquire more nutrients (Craine, 2013). Additionally, nutrient uptake is linked to water availability; plants need an adequate water supply to absorb nutrients (Zotz, 2001). However, since irrigation is supplied in this study, soil water content is similar and there is adequate water across all experimental plots (not higher in the AV plots) and, thus, uptake of nutrients in this study is not related to water availability as affected by the solar panels in the AV plots.

Alternatively, there are other possible explanations for increases in nutrient levels in the leaves of plants in shaded conditions that seem to fit with our data. One reason for the increase in N specifically could be that leaves adapted to low light tend to have larger chloroplasts with more chlorophyll per chloroplast as a physiological response to shade (Diaz-Perez, 2013). And, seeing as N is a major component of chlorophyll, chlorophyll indices are sometimes used to estimate N levels in plants. It is possible that N increases in shaded plants due to more chlorophyll (Diaz-Perez, 2013). Furthermore, when looking at K levels specifically, higher levels of K are often associated with lower transpiration rates (Jin et al., 2011). This increase is because K ions play an important role in regulating the stomatal closure and opening in a plant (Jin et al., 2011). Consequently, in the AV plots where K is equally available and transpiration is lower than in the full sun, K nutrient accumulation could be expected to be higher in plant tissue. Another explanation for the increase of all these nutrients (N, P, and K) in shaded leaves is in response to the modified temperature conditions created by the shade (Diaz-Perez, 2013). Shading can reduce air temperatures around the crops which prevents heat stress from occurring; because there is less heat stress plants (where stomata close) plants increase or continue nutrient uptake (Tindall et al., 1990). For example, studies of tomatoes (*Lvcopersicon esculentum cv.*) in solution culture found that optimal temperature for the uptake of nutrients by the tomato plant is about 25 degrees Celsius (77 °F) (Tindall et al., 1990). With the average summer temperature highs during the day in summer growing months in Amherst, Massachusetts, from 78 °F in June, 82 °F in July, and 81 °F in August ( U.S. Climate Data, 2010) it is possible that a reduction of heat stress under the panels could influence nutrient uptake. Additionally, leaf temperature data discussed further below shows a significant difference on sunny days between crop temperatures in the full sun and under the AV plots. Consequently, in this study, we looked at N P and K to see how nutrients are affected in AV systems because of the different shade levels.

For Swiss chard, it is determined that for N and P, the more- shaded AV plots have statistically higher nutrients in the leaves, but for K there is no trend. The higher level of nutrients N and P in the shaded plots could be the result of a decrease in temperature under the panels so the temperature under the panels is optimal and allows for more nutrient uptake. The increase in N may be a result of an increase in chlorophyll in the shaded plants. For K there is no difference in K levels between the experimental plots which is unexpected because of lower temperatures and transpiration expected in the AV plots than in the control plots.

For kale there is no significant trend in nutrient levels varying with shade level of the experimental plots. For kale K there is a cubic trend that was significant but does not make sense with the data.

For pepper, there is no significant trends in N or P nutrient levels with varying shade in the experimental plots. However, for K there was significantly higher concentrations of K in the AV plot pepper plants than in the control plot pepper plants. For peppers, shade seemed to increase K percent dry weight which could be a result of reduced transpiration rates and there were no trends apparent for N and P.

For broccoli there was no significant trends in N or K nutrient levels with varying levels of shade in the experimental plots. For P there is a linear trend in the AV plots; as shading increases so do the levels of P. The higher P nutrient levels in broccoli that occur in the more shaded conditions may be a result of a decrease in temperatures under the panels to an optimal growing temperature which allows for more nutrient uptake.

In general, for N, P, K, nutrient levels there is no definitive trend for all the nutrients, however within certain crops some trends are evident. In Swiss chard there is significantly higher levels of N and P in the most shaded plots: for Swiss chard the 2-ft gap AV plots had the highest N and P nutrient levels, and for P, the mean P nutrient level is significantly higher in the AV plots than in the control plots, a result that may indicate that Swiss chard is affected by variation in temperature/shade below the panels. For peppers it was found that mean K level is significantly higher in the AV plots when comparing to the control plots. For broccoli there is a linear trend of decreasing P in the AV plots as gap distance between panels increases. Increases in K nutrient levels in the more shaded AV plots may be a result of lower transpiration rates and lower temperatures (not heat stressed temperatures) (Adeh et al., 2018, Amaducci et al., 2018, Marrou et al., 2013c). As mentioned previously, N levels may be increased because of increased chlorophyll in shaded plants (Diaz-Perez, 2013). Also, for all nutrients, shade in some of the experimental plots could have prevented heat stress allowing for nutrient uptake to occur (Diaz-Perez, 2013). It is possible that trend in nutrients are not significant or different because irrigation was constant and may have affected transpiration (especially for K). Moreover, fertilizers are applied in this study to avoid nutrient deficiency which may have affected the levels as well. In the future, a soil test should be done prior to planting to ascertain nutrient availability to the crops is the same in all plots.

### 2.4.4 Soil Water Content

The variation in shading by the panels also may have an effect on the soil water component of the microenvironment below the panels. Specifically, solar radiation is significant in its effect on evaporation and transpiration (Campillo et al., 2012). Evaporation and transpiration are closely related and, thus, often considered together; however, evaporation particularly refers to water loss of water from the soil surface while transpiration refers to evaporation of water from plant organs (generally leaves) (Campillo et al., 2012). The amount of evaporation is determined by, firstly, the amount of water in the surface of the soil and, secondly, by the amount of solar radiation that reaches the surface of the soil (Campillo et al., 2012). Several studies conclude that a reduction in solar radiation causes a reduction in evapotranspiration and results in higher soil moisture in shaded areas (Lin et al., 1999, Marrou et al., 2013, Elamri et al., 2017, Amaducci et al., 2018). This occurrence is because with a reduction in radiation there is also a reduction in evaporative demand placed on the crops that are shaded (Campillo et al., 2012). It is important to note that soil water has an effect on the resultant plant water; lack of water in soil causes a plant deficit in water (Campillo et al., 2012). If a plant does not have enough water its stomates will close to conserve water and photosynthesis will be restricted by impeded gas exchange (Campillo et al., 2012). Consequently, if there are significant differences in soil water content as a consequence of shade, it is possible that photosynthesis and growth of crops would be affected. There has also been work that indicates that the solar panels could influence the distribution of water under the panels. For example, by intercepting precipitation, panels could concentrate rainfall input to the lower lip of the PV panel (Armstrong, et al., 2016).

There is no significant difference overall in soil water content across all the AV plots. Comparing soil water content from all of the AV plots against soil water content in the control plots, there is not a significant difference. It is important to note that all experimental plots are irrigated in this study. Overall, soil water content does not differ with gap distance or area within plot but the gap x area interaction is significant. Separating the interaction by area, because we are most interested in gap, shows that gap is not significant in the left area, but is in the right and middle area. In the left area soil water content is fairly similar across all experimental plots. It is found that for soil water content in just the right area there is no linear, quadratic, or cubic trend in the shaded plots. However, when comparing soil water content for the right area of all the AV plots against the soil water content of the control plots, the control plots soil water content is significantly lower. This result indicates that for the right area within the plots soil water content is higher in the AV plots than in the full sun control plots likely since less evapotranspiration was occurring in the AV plots. This explanation is supported by Marrou et al. (2013c), Elamri et al. (2017), and Amaducci et al. (2018) studies of evapotranspiration that determine that a reduction in solar radiation under panels limits evapotranspiration and increases soil water content in shaded areas. Comparing soil water content for the middle area of all the AV plots against the soil water content of the control plots, the control plots soil water content is significantly higher. The middle area in the AV plots has a sloping panel directly over the soil while the control plots middle area has no panel. This result could be a consequence of the panels interrupting precipitation because we would expect due to reduced evapotranspiration that the areas under panels have higher soil water content. It is possible that panels redistributed rainfall especially because rainfall was particularly high for summer 2018; the average yearly rainfall in Massachusetts is 45.99 inches (U.S. Climate Data, 2010), and in 2018, it was about 61 inches (Swasey, 2019). Perhaps, the panels concentrated rainfall to the lower lip of each panel so that the control area receive more direct rainfall than the areas under the panels (Armstrong, 2016). Furthermore, the control areas are located in front of the panels. All of the plots are irrigated and received same amount of water below panel level.

### 2.4.5 Leaf Temperature

Finally, leaf temperatures of crops can be affected by shade primarily because shade reduces the amount of incoming solar radiation (Parbst, 2010). The temperature of a leaf is representative of the heat energy that is present in the leaf (Greenhouse Management, 2011). The energy of a leaf (temperature increases) rises as a result of intercepted solar radiation and infrared radiation from surroundings while energy of a leaf declines (temperature declines) through emission of infrared radiation from the leaf, convection, conduction, and heat loss because of water evaporation (Greenhouse Management, 2011) An important note to make is that surrounding air temperatures are not indicative of leaf temperature (Greenhouse Management, 2011). The temperature of a leaf can vary greatly (10-30 °F) from ambient air temp as a result of plant and leaf location; however, when the sunlight is blocked, leaf temperatures can drop similar to ambient air temps (Green Management, 2011). In the shade, the temperature of plant leaves can even be lower than ambient air temperatures (Greenhouse Management, 2011) A reduction in solar radiation has been known to cause lower leaf temperatures of plants in shaded areas compared to leaves in the full sun because of less incoming radiation (Lin et al., 1999). However, Valle et al. (2017) finds that the variation in leaf temperature under the panels evens out over the course of the day. Shading reduces air and leaf temperature because of the reduction in solar radiation (Diaz-Perez, 2013). Because shading can reduce leaf temperatures it is possible that it can prevent heat damage in crops; however, it will also reduce photosynthesis (Parbst, 2010).

We examined leaf temperatures of pepper plants in the experimental plots on cloudy and sunny days to see the effect that the solar panels have on temperatures. There is a difference in pepper leaf temperature under the panels in the AV plots versus pepper leaf temperatures in the control plots only on sunny days. On sunny days comparing leaf temperature from all of the AV plots against the leaf temperatures from the control plots, leaf temperatures are significantly lower in the shade of the panels but the gap distance within the AV plots did not affect the leaf temperatures. The reduction in leaf temperature here is consistent with findings that reduction in solar radiation causes lower leaf temperatures because of less incoming radiation (Lin et al., 1999).

On cloudy days for gap distance between panels, there is not a significant difference in leaf temperatures either within the AV plots or when comparing the leaf temperatures of AV plots versus the leaf temperatures of the control plots. This result indicates that on cloudy days, the panels and the full sun control plot receive similar solar radiation levels.

### 2.4.6 Conclusion

In conclusion, based on biomass crop yields for all crops, the control full sun plots have the highest yields. Specifically, kale has a linear increase in biomass with a decrease in shading and broccoli stem + leaf biomass shows a significant increase in biomass in the AV plots versus the control plots. For either broccoli or kale the 4-ft or 5-ft gap AV plots perform the best (have the highest biomass yields) of the AV plots. We conclude that 4-ft and 5-ft distances are optimal of the AV plots for biomass production. There are different performances in crops for the 2018 growing season; growth of pepper fruits is the worst under panels, followed by Swiss chard, whereas kale and broccoli seem to produce yields closer to full sun yields due to the ability to adapt to reduced radiation.

For nutrients, Swiss chard shows significant differences by gap distance between panels; for N and P the 2-ft gap AV plots have the highest nutrient levels, and for P the control plot has lower nutrient levels than the average of the AV plots. For pepper K increases linearly with more shade in the AV plots. For Broccoli in the AV plots P increases linearly with more shade. However, there are not definitive trends across all crops for nutrient levels. These higher levels of nutrients in the more shaded plots indicate that a certain level of shading temperatures may become optimal to stimulate nutrient uptake; no heat stress (Tindall, 1990). N also may have been increased as the result of an increase in chlorophyll in the shade, and K may increase due to lower transpiration rates in the shade (Jin et al., 2011).

Additionally, the microenvironment under the panels in the AV system is found to be affected as well as a consequence of reduced radiation. Leaf temperature is lower for leaves under the panel on sunny days than in the full sun.

Finally, for soil water content there is not a difference by experimental plot. There is, however, a significant interaction between gap and area that indicated panels in the AV system have some effect on evapotranspiration and rainfall redistribution at the soil level.

Ultimately, AV systems can be constructed on farmland in a way that the systems allow for continued agricultural use of the land. This research suggests that some crops are more suitable to be grown under the panels and that a minimum gap spacing of 4-ft is needed to allow sufficient light to pass through gaps between panel spacings. Because rainfall was particularly high for this 2018 study year the experiment should be analyzed over several years with different weather conditions to understand the full effect of the system.

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